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THE GEOLOGY OF THE GOLD OCCURRENCES OF VICTORIA, AUSTRALIA.

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INTRODUCTION.

The total yield of gold from Victoria is about £300,000,000 ($1,458,000,000)[1] divided approximately equally between reefs and placer deposits.

At the present time the gold mining industry is in a languishing state and is in danger of soon becoming a thing of the past. The following figures will serve to illustrate the marked decline during the past 20 years.

Year.	Gold Yield, Ozs.	Dividends Paid.	Dividend Paying Mines.	Men Employed.
1899.....	807,407	£455,332 ($2,212,915)	73	29,035
1919.....	135,427	£ 25,180 ($ 122,374)	9	3,065

The world famed mines of Ballarat, Clunes, Maryborough and Walhalla are all idle and many of them are full of water and probably will not be reopened in the future. Over a large portion of the state all that remains to remind one of an industry which has made Victoria so prosperous, are deserted towns and camps; mullock heaps glistening in the sun; occasional poppet heads; old alluvial workings resembling shell pocked battlefields and an occasional prospector with his pan and pick.

The topography, general geology and structural features of the gold-fields have been examined in considerable detail by members of the Geological Survey. The results of their work which are embodied in the Records, Bulletins, and Memoirs of the Survey, have been briefly summarized by the director, Mr. H. Herman.[1a]

[1] Normal exchange.

[1a] Economic Geology and Mineral Resources of Victoria. Bull. 34, Vic. Geol. Surv., 1914.

Apart from the work of the late Dr. A. W. Howitt and of Professors J. W. Gregory and T. S. Hart; and more recently that of Dr. Stillwell at Bendigo and Costerfield, and of the present writer at Queenstown, Walhalla and Wood's Point, the petrological, mineralogical and genetic aspects of Victorian gold occurrences have received little attention. The object of this paper is to deal with these aspects in some detail.

The writer is indebted to Mr. H. Herman, the director of the Geological Survey, and his officers, Messrs. W. Baragwanath, O. A. L. Whitelaw and A. M. Howitt for assistance on many occasions. He is especially indebted to Mr. W. Baragwanath for the benefit of his valuable experience..

Much valuable information has been extracted from the various publications of the Victorian Geological Survey and from numerous scientific papers. Acknowledgments of these are made wherever possible.

OUTLINE OF GENERAL AND STRUCTURAL GEOLOGY.

The bed rocks of the gold-fields are chiefly of Ordovician and Silurian age. Auriferous ores have been worked in pre-Cambrian metamorphic rocks at several places in North Eastern Victoria and unimportant quartz reefs also occur in a few places in rocks of Devonian and lower Carboniferous age, but no auriferous reefs are known in rocks of more recent age. The Ordovician rocks consist essentially of sharply folded fossiliferous sediments, for the most part sandstones and black slates, the latter often rich in carbon. The well known gold-fields of Western Victoria—Bendigo, Ballarat, Clunes, Maldon, Daylesford, Maryborough and Castlemaine all occur within lower Ordovician beds. The upper Ordovician are widespread in Eastern Victoria but contain few important goldfields. Closely folded Silurian sediments cover a wide area in Central and Eastern Victoria. These are chiefly sandstones, mudstones and shales with occasional bands of coral and crinoidal limestones and conglomerates. The important gold-fields of Walhalla, Wood's Point and Gaffney's Creek occur in these rocks.

The major folds in these older Paleozoic rocks trend from N.E. to N.W. and have an average direction of a few degrees West of North. Dips are usually steep and away from the axes of the folds are rarely less than 45°. Minor folding has been developed in many places along axes at right angles to the major folds.

Contemporaneous with the folding extensive faulting, chiefly of the strike reverse type, took place, and jointing and other fractures were developed in the strata. These earth movements were attended by the intrusion of numerous large bosses of granodiorite and dikes mainly of intermediate and basic composition; the extrusion of andesitic, dacitic and rhyolitic lavas followed. The auriferous veins conform closely in strike with the enclosing sediments and the auriferous belts strike parallel to the strike of the strata. The orogenic movements, vulcanism, and ore formation were closely connected and appear to have occurred in the Devonian period. The Lower Carboniferous beds are only slightly tilted and rest on the upturned edges of the uppermost Silurian beds and older formations; they cover up some of the quartz reefs and associated igneous rocks.

From Devonian to the Tertiary time no marine beds were formed in this region. The Lower Carboniferous sandstones and the Jurassic coal measures represent periods of fresh water deposition.

In early Tertiary time Victoria appears to have been planed down to a relatively low lying land surface with extensive coastal plains covered by lagoons and swamps in which deposits of clays and lignites were formed. Further inland, much of the gold derived from the disintegration of the former upward extensions of the auriferous reefs was being concentrated in the highly quartzose sands and gravels forming the beds of lakes and matured rivers. Some of the gold remained in situ at or close to the outcrops of the reefs. Where conditions were favorable, part of it was reconcentrated by solution and precipitation in the zone of oxidation, but the bulk of the gold was carried away into the streams.

In Miocene (?) time flows of basalt filled up many of the river valleys in Eastern Victoria, burying in some cases richly auriferous gravels. During and following these outpourings of so called "older basalt" there apparently was a general subsidence of the land accompanied by marine transgression over the greater part of the northern, western and southern margins of the state. As a result of this subsidence many river valleys with richly auriferous gravel beds were deeply buried under layers of clay and sand. Among these are Avoca valley and those near Rutherglen and Chiltern and others near Stawell, Alexandra, Beaufort, Dunolly and Pitfield.

In late Pliocene (?) time the land gradually emerged from the sea and was elevated. The extent of uplift progressively increased going from west to east across Victoria and probably amounted in the eastern part of the state to nearly 6,000 feet. A new cycle of active erosion and gold concentration was thus inaugurated. The enriched outcrops and oxidized zones of the reefs were deprived of much of their gold which was carried into the streams and there supplemented by the gold derived from previously formed gravels and sands. At an early stage in the uplift Western Victoria was covered by widespread sheets of newer basalt which buried the rivers forming the extremely rich deep leads of the Loddon Valley, Ballarat, Daylesford, Ararat, and others.

TYPES OF IGNEOUS ROCKS ASSOCIATED WITH AURIFEROUS ORES.

General.—In many gold-fields of Victoria there is an intimate connection between auriferous ores and igneous intrusions. Most commonly the ores are related to lamprophyre and diorite porphyrite dikes but some are associated with granodiorite intrusions and quartz porphyry dikes and rarely with rocks of basaltic composition.

Granodiorites.—Large intrusions of plutonic rocks which are generally classed as granodiorite but which in part may be quartz monzonite are found in close proximity to nearly all the prin-

cipal gold-fields: Bendigo, Ballarat, Maldon, Castlemaine, Stawell, Clunes, Harrietville, and Walhalla. The intrusions have contract metamorphic aureoles. Daylesford is apparently an exception as the nearest granitic rock comes to the surface some 12 miles away. In general the granodiorites are medium to coarse grained rocks in which plagioclase felspar, biotite and quartz are visible in hand specimens.

Felsites and Quartz Felspar Porphyries.—Dikes of felsite and quartz felspar porphyries are directly associated with auriferous reefs at Maryborough, Maldon, Stawell, Ballarat, Blakeville near Ballan, Foster and in the Yarra and Mitta-Mitta gold-fields. In general they conform closely to the strike of the sediments in which they are intruded. Viewed broadly their age is Devonian as they are intrusive into the uppermost beds of the Silurian series and are overlain by beds of Lower Carboniferous and Permo-carboniferous age. Porphyritic phenocrysts of quartz and felspar are recognizable in some specimens but more often they are yellow green aphanitic textured rocks. Under the microscope phenocrysts of corroded quartz, skeleton felspar crystals now replaced by densely matted aggregates of sericite, and occasional prisms of bleached biotite including rutile needles are seen in a cryptocrystalline ground mass composed essentially of quartz, sericite, and often some albite. Crystals of pyrite are not uncommon but carbonates are rare.

Diorite and Gabbro Porphyrites and Lamprophyres.—These rocks are closely connected with auriferous reefs in many parts of the colony. They are best known from the Walhalla-Wood's Point belt where they are very prominently developed, but they also occur in the Pyrenees belt; in the belt extending from Creswick through Maryborough, Dunolly and Wedderburn, in the Alexandra-Tanjil belt; in the Wandiligong and Mitta-Mitta belts and also at Dargo, Grant, Queenstown and elsewhere.

Normally the diorite and gabbro porphyrites occur as elliptical dike expansions which agree closely with the general structure of the sediments through which they are intruded. The well known Morning Star dike at Wood's Point is typical of these intrusions.

It is elliptical in plan, having maximum dimensions of 1,700 feet by 280 feet; shows no diminution in width in depth and cuts across the strata at a low angle. Hand specimens of these rocks are medium and fairly even grained. The predominant macroscopic minerals are hornblende and felspar but quartz, biotite, augite, chlorite, carbonates and pyrite can be identified in some specimens. Typical thin sections viewed microscopically consist predominantly of phenocrysts of chloritized brown hornblende, chloritized and sericitized plagioclase (andesine and labradorite) in a matrix of granular and prismatic hornblende, felspar laths, ilmenite grains and interstitial quartz, albite, and intergrowths of quartz and felspar. Biotite and augite are often present. The alteration products characteristic of propylitization are never entirely absent. These include: chlorite, epidote, leucoxene, carbonates and the sulphides pyrite and pyrrhotite.

Narrow dikes of hornblende and biotite lamprophyres are frequently accompanied by auriferous quartz reefs in Victoria. Normally they are grey or green colored fine-grained rocks. Without exception they are more or less hydrothermally altered and occasionally the alteration has been so intense that their original characters are indeterminate. Chlorite, carbonates, sericite, leucoxene, and pyrite are the usual secondary minerals. The chemical composition of these lamprophyres correspond closely with those of the diorite and gabbro porphyrites into which they sometimes pass.

Basalt and Diabase.—At the Coronation mine, Walhalla, rich quartz veins have been worked in an intrusive pipe of prophyritic basalt which grades interiorly into a granophyric gabbro porphyrite. The intrusion is roughly circular in plan,[2] 850 feet by 750 feet; its walls are nearly vertical and it is believed to be of Devonian age.

At the Great Rand mine, near Mansfield, lenses of auriferous siliceous sulphide ore occur within hydrothermally altered diabase lavas of Cambrian age.

[2] W. Baragwanath, The Coronation Gold Mining Company, Walhalla Rec., Vic. Geol. Surv., vol. 3, Part 3, p. 269, 1914.

METASOMATISM ACCOMPANYING ORE FORMATION.

General.—The igneous rocks associated with the auriferous ores are invariably more or less altered. Apart from weathering two distinct types of metasomatic alteration can usually be recognized in such rocks.

1. A widespread regional permeation of the rocks—quite independent of the vein fissures—by thermal waters probably of magmatic origin.

2. Hydrothermal alteration of the wall rocks adjoining the veins.

Regional Alteration.—This type of alteration is believed to have taken place before the rocks had cooled sufficiently to fracture. The effects of the hydrothermal vein alteration are superimposed upon those of the regional alteration. Two phases of the latter have been noted in certain diorite porphyrite and lamprophyre dike rocks of the Walhalla-Wood's Point belt.

1. A late magmatic phase caused by the squeezing of residual siliceous and alkaline carbonate waters through the cooling igneous rocks. As a result some albite is developed at the expense of the original calcic felspars, the femic minerals in part are bleached, actinolitic and tremolitic outgrowths form on the hornblende and interstices in the rock are filled with quartz and micropegmatite.

2. Propylitization: As a slightly later phase of the same alteration the characteristic minerals of propylitization, namely abundant chlorite (pennine), some carbonates, albite, leucoxene, pyrite, and pyrrhotite and in certain cases epidote, clinozoisite and some sericite, are developed. The femic minerals—hornblende, augite and biotite—are extensively chloritized and sometimes carbonates and epidote replace them in part. Rutile and titanite often separate from these femic minerals on their alteration to chlorite. Albite is often developed from the soda lime felspars and in some cases chlorite, clinozoisite, epidote and a little sericite replace them. Ilmenite is changed to leucoxene which in turn is partly replaced by pyrite and pyrrhotite.

On the whole the chemical changes caused by the regional alteration are small. The largest increases are seen in the percentages of water, carbon dioxide and sometimes sulphur, but soda and silica appear to be slightly augmented.

Hydrothermal Alteration.—Adjoining the veins for varying distances but usually less than two or three feet the wall rocks have been altered by the vein solutions. Near veins within igneous rocks the effects of the alteration are a bleaching and reduction in the grain of the rocks and the development in them of pyrite and arsenopyrite and rarely stibnite, in amounts decreasing outwards from the vein walls.

The nature of the chemical and mineralogical changes brought about by this alteration have been most thoroughly studied in the rocks from the Walhalla-Wood's Point belt.[3] The diorite porphyrites and lamprophyres, are composed essentially of hornblende, plagioclase felspar, ilmenite and quartz and locally biotite, augite and orthoclase. Near the veins they are altered to grey and greenish yellow rocks consisting principally of ankerite, sericite, quartz, and albite accompanied by some pyrite, arsenopyrite, and rutile. With the exception of some quartz and apatite all the minerals of the propylitized rocks have succumbed to the intense chemical activity of the vein waters. As usual, the femic minerals, in the order hornblende, biotite, augite, are the first to disappear. Chlorite disappears close to the vein walls and its place is taken by carbonates and sericite for the most part. Fine pseudomorphs of carbonates and sericite after hornblende, augite, and biotite can often be recognized. Normally the felspars become highly sericitized but sometimes they give rise to fresh albite. Leucoxene and granular sphene replace the ilmenite and they in turn are frequently replaced by pyrite and carbonates. The carbonates of the vein altered wall rocks are dusty and granular and quite distinct in character from the interstitial and massive carbonates of the propylitized rocks. The intensity of carbonation appears to vary directly with the basicity of the

[3] Junner, N. R., The Geology and Ore Deposits of the Walhalla-Wood's Point Gold Belt, *Proc. Austr. Inst. of Min. and Met.*, 1920.

original rock. The accompanying analyses Nos. 3 to 10 illustrate clearly the nature of the hydrothermal vein alteration.

TABLE I.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
SiO_2.....	71.16	76.25	49.65	39.92	48.47	44.45	48.06	42.73	56.91	41.03
Al_2O_3	10.19	15.12	16.73	14.81	17.50	16.17	19.86	10.86	13.31	25.16
Fe_2O_3.....	0.36	1.86	0.31	0.61	0.61	1.95	0.54	0.60	0.08	8.61
FeO	0.68	tr	7.87	5.81	8.55	6.62	7.52	6.46	5.33	
MgO	0.60	0.18	5.88	6.80	4.51	3.70	3.13	10.14	3.66	4.02
CaO.....	1.77	tr	7.87	8.28	8.41	4.98	6.86	6.16	3.38	0.56
K_2O	2.03	3.10	0.80	3.51	1.23	2.76	0.99	1.80	3.76	5.36
Na_2O	4.73	1.37	3.10	1.41	2.73	2.57	3.96	1.84		1.33
H_2O+	2.17	1.61	2.50	1.03	3.10	1.68	2.21	0.81	1.19	3.86
H_2O-	0.22	0.10	0.14	0.23	0.07	0.31	0.30	0.28	0.13	0.66
TiO_2.....	0.11		2.81	1.26	2.45	2.10	1.82	1.22	1.40	1.12
CO_2..	pnd		1.08	16.38	0.90	11.23	3.33	16.05	9.75	2.64
P_2O_5.....	tr		0.04		0.32	0.70	0.10			0.31
MnO	tr	tr	0.14	0.09	tr	0.15	0.12		0.23	tr
FeS_2.....		SO .92	tr	st tr	0.81	0.93	0.92	0.54	0.85	2.79
Sb & As...		pnd								C.2.58
Cr_2O_3.....							0.03			
(NiO)CoO			tr	tr	nil	nill	tr			
SO_3.....					nil	tr				0.32
Cl.....	tr				nil	tr				tr
BaO.....	tr				tr	tr	0.05			
		100.51								
less O=S		0.34								
Totals ..		100.17	100.04	100.14	99.66	100.30	99.80	99.49	99.98	100.38

1. Light-colored felspathic dike, Crown Cross mine, Stawell. Analyst, P. G. W. Bayly.[4]

2. Altered quartz felspar porphyry dike, 800-foot level, Diamond Creek mine, near Melbourne. Analyst, N. R. Junner.[5]

3. Propylitised diorite porphyrite—10 feet from Cherry's reef, Hope adit level, Morning Star dike, Wood's Point. Analyst, N. R. Junner.[5]

4. Vein altered diorite porphyrite—within one foot of Cherry's reef, Hope adit level, Morning Star dike. Analyst, N. R. Junner.[6]

5. Propylitised diorite porphyrite—5 feet from quartz "floor," No. 1 level below No. 5 adit level, New Loch Fyne mine, Matlock. Analyst, F. Moss.[6]

6. Vein altered diorite porphyrite from within one foot of the quartz "floor" mentioned above. New Loch Fyne mine, Matlock. Analyst, J. C. Watson.[7]

7. Propylitised hornbende mica lamprophyre (camptonite) 10 feet from quartz "floor," 850-foot level, A. 1. mine, Gaffney's Creek. Analyst, N. R. Junner.[7]

8. Vein altered hornblende mica lamprophyre adjoining quartz "floor," 850-foot level, A. 1. mine. Analyst, N. R. Junner.[7]

9. Vein altered A. 1. dike close to quartz "floor," No. 9 Intermediate level, A. 1. mine. Analyst, N. R. Junner.[8]

10. Altered slate from the wall of a laminated quartz reef in the Central Blue back, 556-foot level, Sheepshead mine, Bendigo. Analyst, F. Moss. The end point of the FeO determination was obscured by suspended particles of carbon.[9]

The characteristic features of the vein alteration are the considerable increases in the percentages of carbon dioxide and potash, and the marked reduction of the amounts of water, titanium dioxide, and in places of soda. In addition there are small but constant decreases in silica, alumina, and ferrous oxide. On the whole the amounts of lime, magnesia and ferrous oxide are not greatly changed. This is due to the fixing of these bases in the altered rocks in the form of ankerite. The theoretical amount of CO_2 required to fix the whole of these bases in analysis No. 9, is 9.82 per cent. which very closely approaches the amount determined by analysis, *i.e.*, 9.75 per cent.

The large reduction in the water percentage is explained by the replacement of chlorite by sericite and carbonates. The reversal of the alkalies is not so complete in analyses No. 6 and 8 as in Nos. 4 and 9, due to the development of some fresh albite 6 and 8.

Analysis No. 9 appears anomalous in some respects. Microscopical examination of a thin section of the rock shows however that it is the vein altered facies of a rock much more acid than the normal hornblende mica lamprophyre.

The calculated approximate mineral compositions of some of these vein altered rocks are given in Table II.

Analyses Nos. 1 and 2, Table I., although from different locali-

[4] E. J. Dunn, *op. cit.*, p. 9.

[5] N. R. Junner, General and Mining Geology of the Diamond Creek Area, *Proc. Roy. Soc. Vic.*, vol. XXV (n. s.), Part *II*, 1913, p. 340.

[6] *Idem.*

[7] N. R. Junner, *Loc. cit.*, 1920.

[8] N. R. Junner, The Petrology and Mining Geology of the Country near Queenstown. *Proc., Roy. Soc. Vic.*, vol. 27 (n. s.), 1914, pp. 123 and 131.

[9] F. L. Stillwell, Gold Deposition in the Bendigo Gold Field. Bull. 16, Advisory Council of Science and Industry, Melbourne, 1919, p. 13.

TABLE II.

	1.	2.	3.
Sericite[1]	29.75	23.40	40.0
Ankerite	35.82	25.54	22.2
Albite	11.92	21.72	
Quartz	16.30	16.70	35.4
Anorthite	2.86		
Rutile		1.79	1.4
Leucoxene	3.09	0.77	
Apatite		1.54	
Pyrite		0.93	0.85
Kaolin		4.50	
Excess Al_2O_3		1.14	
Fe_2O_3	0.61	1.95	0.08
Totals	100.35	99.98	99.93

1. Vein altered diorite porphyrite, Morning Star Dike, Wood's Point; within one foot of Cherry's reef—Hope adit level.

2. Vein altered biorite porphyrite—New Loch Fyne Dike, Matlock, within one foot of quartz "floor," No. 1 level below No. 5 adit level.

3. Vein altered dike close to quartz "floor," No. 9 Intermediate level, A. 1. mine.

ties indicate in a general way a different type of vein alteration characteristic of certain quartz and felspar porphyries and felsites—associated with the auriferous reefs. The least altered rocks which consist of phenocrysts of quartz, orthoclase, albite and usually a little biotite in a microcrystalline or cryptocrystalline matrix composed chiefly of quartz, albite and sericite are changed to quartz sericite rocks impregnated with some pyrite and occasionally arsenopyrite. Carbonates are usually lacking or uncommon. Chemically the chief additions are in the percentages of potash, sulphur and silica. Water, soda, lime, magnesia, and ferrous oxide are all markedly reduced.

Where sedimentary rocks form the wall rocks of the reefs they usually show distinct evidence of alteration. The visible effects are the development of pyrite, arsenopyrite, and carbonates. Arsenopyrite normally is more abundant in slate wall rocks than in sandstones and the latter are often silicified. Thin sections of the wall rocks rarely fail to reveal also much sericite. Albite has also been noted in isolated cases.

[10] Theoretical muscovite.

Analysis No. 10, Table I., represents a vein altered carbonaceous slate from Bendigo. The approximate mineral composition computed from the analysis is as follows.

TABLE III.

Sericite	45.42	Rutile	1.12
Kaolin	12.97	Apatite	0.73
Albite	11.24	H_2O	0.66
Fe_2O_3	8.61	SO_3	0.32
Quartz	6.75	Excess MgO	1.62
Carbonate	5.04	Excess Al_2O_3	0.35
Pyrite	2.79	Excess CaO	0.15
Carbon	2.58	Total	100.35

The amount of free silica (quartz) is relatively small. A little sulphate is apparently present.

CLASSIFICATION AND DESCRIPTION OF ORES.

The auriferous ores of Victoria may be conveniently classified as follows:

Ores directly associated with igneous rocks.
- Ores with plutonic rocks.
  - Reefs within plutonic rocks.
  - Auriferous pegmatites.
  - Ores in contact aureoles of plutonic rocks.
- Ores associated with dikes.
  - Ladder veins.
  - Fault reefs intersecting and associated with dikes.
  - Fissure reefs on walls of dikes.
  - Stockworks.
- Ores in volcanic rocks.

Ores not directly associated with igneous rocks.
- Bedded reefs—Saddle and inverted saddle reefs and leg reefs.
- Fault reefs.
- Spurry formations.
- Pyritic and siliceous replacement ores.

Placer deposits.[11]

[11] While placed here for the purpose of completeness in classification, their description is deferred to the end of the paper.

Ores Directly Associated With Igneous Rocks.

Ores with Plutonic Rocks.—Auriferous ores occur in plutonic rocks mainly of granodiorite composition, at Mt. William near Stawell, Maldon, Dargo, Mt. Wills, Hillsborough, Warburton and elsewhere. Normally the ores are simple veins and stockworks and rarely are of any economic importance.

Auriferous pegmatites are known from Huon's Lane near Wodonga, N.E. Victoria, Maldon and from Linton's near Ballarat. They have yielded little gold and are chiefly of scientific interest.

Certain ores occur in the contact metamorphic aureoles of plutonic rocks mainly of granodioritic composition. The richest and most productive deposits of this type are those of Maldon. Here the ores occur as well defined steeply dipping lenticular strike reefs in hornfels, quartzite, and schists of Lower Ordovician age containing the following minerals: cordierite, andalusite, tourmaline, hornblende, and biotite. One or two of the reefs appear to have penetrated the underlying granodiorite but in general they decrease in size and feather out near the contact. High temperature minerals such as garnet, apatite, hornblende, biotite, pyrrhotite, and molybdenite have been recorded from certain of the reefs.

Ores with Dikes.—This is a very important class and includes among others the well known Cohen's reef at Walhalla, which has yielded more than £5,000,000 ($24,300,000) of gold; the Morning Star, A.1. and New Loch Fyne reefs near Wood's Point; the Mariner's, Leviathan and Blucher's reefs near Maryborough; and the Oriental reef near Wandiligong. The quartz reefs associated with such dike rocks occur as follows:

1. **Ladder Veins.**—These are within dikes. They are flat and apparently disconnected veins of quartz—in fissures which are probably of contraction origin. They usually end abruptly at the dike walls. The best examples are known from the Walhalla-Wood's Point belt. They are particularly well developed in many of the narrow lamprophyre dikes such as the

May Moon and Waverly near Wood's Point, the Georgia at Enoch's Point and Hunt's at Gaffney's Creek. Certain of the flat reefs or "floors" in the dike expansions are apparently of the same nature. These include the Morning Star, Wood's Point, and the New Loch Fyne at Matlock.

2. **Fault Reefs.**—Many of the reefs in the dike bulges of the Walhalla-Wood's Point belt occupy faults which displace the

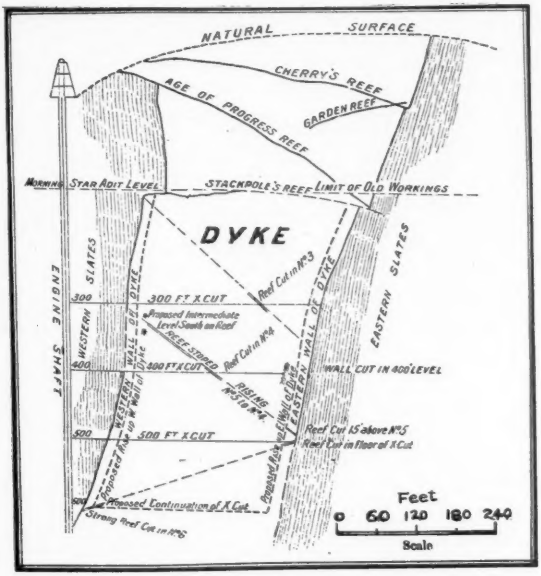


FIG. 14. Transverse section across Morning Star dike, Woods Point, showing irregular alternating east and west dipping reefs. (After Whitelaw.)

dikes as much as 40 or 50 feet. The rich Age of Progress reef, for instance, in the Morning Star dike shifts the dike about 40 feet. Reefs in strike faults which intersect and displace narrow lamprophyre dikes are numerous in the same belt and also at Alexandra, Tanjil and elsewhere. Cohen's reef at Walhalla is a well defined fault reef in close association with a highly carbon-

ated and sericitized lamprophyre dike. It has been worked profitably to a depth of 3,625 feet. Other examples are the All Nations reef at Matlock and certain reefs in the Harrietville and Wandiligong districts.

3. **Reefs on Walls of Dikes.**—The reefs are usually narrow and well defined, and often very rich. In nearly all cases they are associated with either altered quartz felspar porphyry or lamprophyre dikes. At the Oriental mine Wandiligong, from which about £1,000,000 ($4,860,000) gold was extracted and at Diamond Creek, Grant, Derby mine, Maldon and at certain mines near Maryborough the reefs are present on both walls of the dikes. More often the reefs occur on one wall only as at Stawell, Jamieson, Queenstown and Maryborough.

4. **Stockworks.**—Stockworks have been mined in dikes at the Rose of Denmark, Hunt's, and A.1. mines near Gaffney's Creek and have been fairly productive.

Ores in Volcanic Rocks.—The few known examples of auriferous ores in volcanic rocks are of little economic importance. At the Great Rand mine, Mt. Buller near Mansfield, auriferous siliceous sulphide ores which were fairly rich near the surface occur in flows of diabase of Cambrian age; near Gembrook, Healesville, Marysville, and the Snowy river small quantities of gold have been won from streams flowing over dacite lavas probably of Devonian age.

Ores Not Directly Associated With Igneous Rocks.

Many of the principal gold fields of the state such as Bendigo, Ballarat, Clunes, Stawell, and Daylesford fall in this class. Although igneous rocks are not directly connected with the ores, in nearly all cases they are not far removed geographically from intrusions of granodiorite. The more important deposits of this class may be classified structurally as follows:

Bedded reefs including saddle and inverted saddle reefs and leg reefs.

Fault reefs.

Spurry formations.

Pyritic and siliceous replacement ores.

Bedded Reefs.—Bedded reefs are typically developed at Bendigo where they have been highly productive. The general features of the saddle reefs are well known. Recently Dr. Stillwell has studied these reefs in considerable detail and the following descriptions of them are in the main extracts from his papers.[12] Stillwell recognizes two forms of saddle reefs at Bendigo.

(*a*) Symmetrically arched reefs not associated with overlying faults.

(*b*) Arched reefs more or less triangular in cross section formed underneath the intersection of strike faults with centre country (anticlinal axes). The strike fault usually continues down one of the legs of the saddle as a masked fault. As many as 24 saddles have been passed through in a depth of 2,200 feet.[13] The reefs are laminated and brecciated in places and Stillwell regards them as being formed for the most part by a combination of replacement of the wall rock—slates and sandstones—and by growth from small fractures. The best gold shoots appear to occur immediately over the saddle or a little way down one of the legs which is usually the east leg. Normally, the gold is localized near the walls of the reefs particularly along the laminations in the quartz. Saddle reefs have been worked with profit at several other fields notably Clunes, Castlemaine, Berringa, Harrietville and Lauriston. Rich inverted saddle or trough reefs have been worked at Lauriston and at Bendigo. Leg reefs are persistent bedded reefs of fairly uniform width. At Bendigo they are sometimes identical with the legs of saddle reefs. They are usually well laminated and the bulk of the gold normally occurs along the lines of laminations. Stillwell[14] claims that the leg

[12] Stillwell, F. L., Gold Deposition in the Bendigo Gold Field. Bulls. 4, 8, 16, Advisory Council of Science and Industry, Melbourne, 1917, 1918, 1919.

[13] H. Herman, Economic Geology and Mineral Resources of Victoria. Bull. Geol. Surv. Vic., 34, 1914, p. 19.

[14] *Loc. cit.*, Bull 8, p. 31.

reefs at Bendigo have originated for the most part by replacement of the adjoining slates and sandstones. The black carbonaceous laminæ are regarded by him[15] as representing the undissolved carbonaceous residue of the slate which is thrown aside, to the boundary of the quartz crystals. While this explanation of the laminations may be the correct one at Bendigo it is more probable that in other fields, as Ballarat, Daylesford, Walhalla, Clunes, etc., they represent unreplaced scalings and films of the wall rock between sheeted fractures filled with quartz. Leg reefs have also been profitably worked at Ballarat West, Castlemaine and Clunes.

The total yield of gold from Bendigo is approximately 20,000,000 ounces, of which total more than half has been won from bedded reefs.

Fault Reefs.—Typically the fault reefs occur in strike reverse faults which are genetically related to the folding of the strata. Reefs in faults normal to the strike of the strata are exceptional. The Jubilee lode at Scarsdale, apparently, belongs to the latter type.[16] The central portion of fault reefs usually consists of milk white unlaminated or slightly laminated quartz, while near the walls included brecciated fragments of the wall rock are often abundant. Well laminated quartz is exceptional. In general the reefs appear to have been formed by a combination of simple fissure filling and replacement. Typical examples of fault reefs are the so called "leather jackets" of Ballarat East and the "verticals" of Daylesford. The leather jackets are large north and south strike reverse faults which dip about 45° to the west. Large low grade lenticular bodies of quartz mixed with altered country rock occur on the hanging walls of these faults and have been extensively worked. The "verticals" are well defined quartz reefs in strike reverse faults which dip to the west at angles of between 40° and 60° and cut across east dipping strata. They include abundant brecciated and rounded fragments of the wall rock. Fault reefs have also been worked in several other

[15] *Loc. cit.*, Bull. 4, p. 34.
[16] H. Herman, *loc. cit.*, p. 16.

fields, notably Maldon, Berringa and Scarsdale, Bendigo, Castlemaine and St. Arnaud.

Spurry Formations.—These are irregular bodies of quartz—usually connected with bedded or fault reefs and often flat. They cut the bedding planes of the strata. In most cases they appear to have grown in cracks resulting from the fracturing of the beds during folding. The highly productive spurs and flat "makes" of Bendigo, Castlemaine, Ballarat and Daylesford are of this nature. At Bendigo according to Stillwell[17] the spurs are generally found in east dipping strata in the vicinity of the intersections of east and west dipping strike faults. He regards them as growing chiefly from fractures by pushing their walls apart, and partly by replacement. The large well-defined flat reefs of Stawell may belong here but it is more probable that they are fault reefs.

Pyritic and Siliceous Replacement Ores.—The lode at the Magdala mine at Stawell consists of irregular lenses—in places more than 100 feet wide—of siliceous, sulphide ore within highly crumpled metasomatically altered chloritic, graphitic and micaceous schists and calcareous quartzites probably of lower Ordovician age. The schists within the zone of mineralization are highly carbonated, silicified, and sericitized. The gold occurs in ramifying stockworks of veinlets of quartz which contain much pyrite and pyrrhotite and a little ankerite; and in bunches and grains of pyrrhotite and pyrite which thickly impregnate the schists within the lode channel. Free gold is rarely seen, yet about one third of the total recovered is obtained by amalgamation. At present ore averaging about 5 dwts. per ton is being mined.

MINERALOGY AND PARAGENESIS.

Mineralogy.

Typically the auriferous ores of Victoria are ordinary quartz reefs carrying less than 2 per cent. of sulphide minerals and gold.

Quartz greatly preponderates over the other gangue minerals.

[17] *Loc. cit.*, Bull. 8, p. 42.

It is usually milk white or glassy in appearance. In bedded reefs it is characteristically laminated and in fault reefs brecciated, due to unreplaced inclusions of the wall rock. Vugs and comb structure are not uncommon particularly in the massive quartz which fills simple fissures.

Carbonates are rarely absent from the reefs. They vary in composition from calcite to siderite but are usually ankerite. The most obvious characteristic of the vein carbonates is their constant appearance along the contacts of quartz with materials of dissimilar composition, as the lining of the vein walls in slates, sandstones, and dike rocks; and encrusting included brecciated fragments and films of the wall rocks in the quartz veins. In addition they sometimes occur in vugs and as laminations and patches in the quartz.

TABLE IV.

	1.	2.	3.	4.
SiO_2	small	4.48	—	1.52
Fe_2O_3	0.29	1.50	tr.	3.10
FeO	3.08	12.04	6.49	32.15
MgO	2.40	11.12	18.20	14.70
CaO	49.05	28.29	29.04	7.26
MnO	1.68	0.80	0.47	tr.
CO_2	43.06	41.80	45.97	41.51
Totals	99.56	100.03	100.17	100.24

1. Carbonate from a poor section of the Garden Gully, 1,552-foot reef, occurring as massive lumps irregularly in the reef.—Analyst, P. G. W. Bayly.[19]

2. Carbonate associated with payable gold in the east leg of a saddle reef at 890 feet, Constellation Mine. Analyst, Miss M. K. Evans.[20]

3. Carbonate in vein in dike near rich gold—220-foot level, Little Comet mine, Wood's Point. Analyst, N. R. Junner.

4. Carbonate crystals from a vug in the 1,137-foot saddle reef, Johnson's No. 2 mine. Analyst, Miss M. K. Evans.[21]

The composition of the vein carbonates at Bendigo and Wood's Point is illustrated by Table IV.

Albite is met with in auriferous quartz veins on many Victorian

[19] F. L. Stillwell, *loc. cit.*, Bull. 4, p. 20, 1917.

[20] F. L. Stillwell, *loc. cit.*, Bull. 8, p. 10, 1918.

[21] *Idem*, p. 10.

gold fields, *e.g.*, Ballarat, Daylesford, Maryborough, Talbot, Clunes, Maldon, Bendigo, Wood's Point, Gaffney's Creek and elsewhere. Locally as at Ballarat it is a prominent constituent of the reefs. Normally it occurs in massive form in the solid quartz but occasionally it is found in vugs. In certain mines at Ballarat East masses of kaolin probably representing decomposed albite were found in the reefs at depths as great as 1,200 feet.

A dark green vermicular chlorite is a not uncommon constituent of the reefs particularly of the Western gold fields within lower Ordovician slates and sandstones. Stillwell[22] claims that at Bendigo the chlorite represents white mica which has been altered by the mineral solutions. In another place Stillwell[23] states that "The chlorite in its turn may be decomposed by the mineral solutions with the production of ankerite." Where the reefs occur within black slates, carbonaceous matter is often present in them. Sericite and occasionally garnet, apatite, scheelite, tremolite, biotite, tourmaline, rutile and zeolites are also found in the reefs.

Of the metallic minerals pyrite, arsenopyrite, galena, sphalerite, pyrrhotite, stibnite, chalcopyrite, bournonite, and gold are most prominent. Tetrahedrite, jamesonite, boulangerite, bismuthinite, and native bismuth are sometimes present in small quantities in rich shoots of gold, and in certain reefs within and in close proximity to granitic rocks. Molybdenite, wolfram, magnetite and hematite appear.

With few exceptions the gold in the reefs is free milling. Normally it occurs in the form of bright yellow hackly grains locally called "colors." Well-formed crystals, mostly rhombdodecahedra, were fairly common in the reefs at Ballarat East at depths as great as 1,300 feet, but elsewhere their occurrence in depth was exceptional. A characteristic feature of Victorian gold is its high quality. The average fineness of reef gold recovered by amalgamation is about 900 and that of alluvial gold still higher. Gold tellurides have not been recorded from any of

[22] *Loc. cit.*, Bull. No. 4, p. 61.
[23] *Loc. cit.*, Bull. No. 16, p. 11, 1919.

the fields although tetradymite is known to occur in certain reefs at Maldon at which place the rare mineral maldonite, a compound of gold and bismuth containing about 65 per cent. of gold, has been found in several mines.

The gold is rarely distributed uniformly through the veins. Certain situations indicated below are more favored than others.

1. In general the richest gold is found in the quartz close to the vein walls. Such quartz is frequently formed by replacement of the wall rocks and normally contains undigested fragments and residues from the rock replaced and also much finely divided pyrite and arsenopyrite. Without doubt these residues and sulphides have caused the precipitation of the gold in many cases.

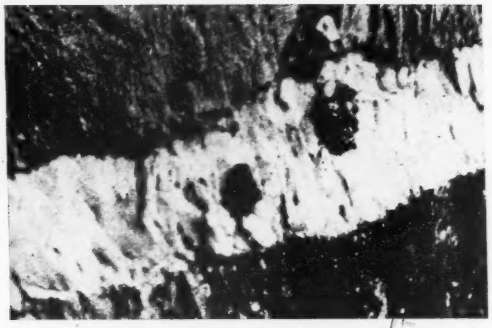
2. Almost invariably in laminated veins the bulk of the gold is aggregated along the carbonaceous, slaty, or pyritic laminations.

3. In veins including brecciated fragments of the wall rock a marked aggregation of the gold is often evident around the margins of these inclusions.

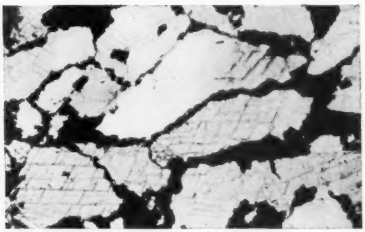
4. In most veins the gold is intimately associated with certain minerals, usually sulphides, which frequently serve to indicate the proximity of rich gold. Viewed broadly the favorable minerals at Ballarat, Bendigo, Clunes, and Castlemaine are sphalerite, galena, and carbonaceous matter; at Maldon stibnite, arsenopyrite, and sphalerite; at Daylesford pyrite, carbon, and boulangerite (?), and in the Walhalla-Wood's Point belt bournonite, arsenopyrite, and tetrahedrite. Throughout Victoria carbonaceous matter in and adjoining the reefs is generally favorable for gold.

Of the sulphide minerals in the veins pyrite and arsenopyrite are the most abundant and most widely spread. They are invariably auriferous and although on most fields they constitute less than 2 per cent. of the ore mined, it generally pays to collect them.

Galena and sphalerite normally accompany one another. In general they are sparsely disseminated through the veins in



a



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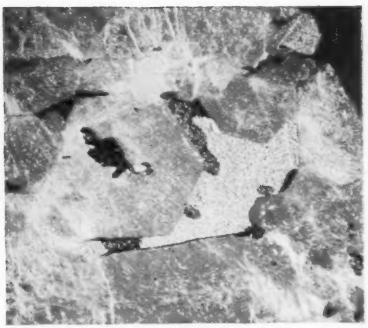


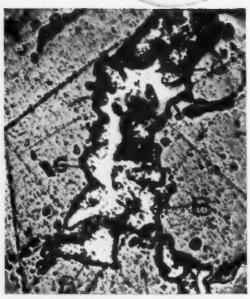
c

a. Coarse gold (black patches in the white quartz) in a flat vein at its intersection with the indicator; 700-ft. level, New Normanby Mine, Ballarat East, from "Victoria: Its Mines and Minerals," 1899.

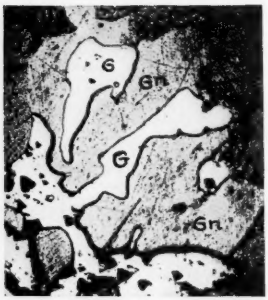
b. Gold in ankerite; 220-ft. level, Little Comet Mine, Wood's Point; shows gold (black) traversing cleaved ankerite, with a colorless quartz. × 25.

c. Auriferous quartz, No. 8 level, A. I. Mine, Gaffney's Creek; shows association of the light gold with bournonite (black) and subsequent origin to idiomorphic quartz crystals on which they are moulded. × 25 reflected light.

a



b



c

a. Face of Lawson's drive, May and Moon dike, adit level, All Nations Mine, Matlock; shows flat "floors" or "ladder veins" of quartz in the dike. After O. A. L. Whitelaw.

b. Microphotograph of a polished section of gold in galena, Virginia Mine, Bendigo. Gold (*g*), galena (*gn*), quartz (grayish black). × 10.

c. Gold (*g*) closely associated with bournonite (*b*) in quartz (gray); 900-ft., A. I. Mine, Gaffney's Creek. × 12.

irregular grains and masses and are usually subordinate to pyrite and arsenopyrite. At places in the Pyrenees belt however they predominate over all other vein minerals, even quartz. They are sometimes rich in silver but rarely contain much gold. Where galena is prominent in the veins the fineness of the gold recovered by amalgamation is invariably low.

Pyrrhotite is a high temperature mineral and is found in greatest prominence in auriferous ores within and in the immediate vicinity of granitic rocks, as at Maldon, Stawell and Mt. William, and in metamorphic rocks as at Bethanga and Stawell. It is occasionally met with in reefs far removed from igneous rocks as at Bendigo and Ballarat but only in minor quantities. The minerals that most commonly accompany pyrrhotite are pyrite and chalcopyrite.

Stibnite is most prominent in the auriferous quartz veins of the Silurian area of central Victoria as at Yarra gold fields, Alexandra, Rushworth and Whroo, and Costerfield. It also occurs in minute quantities in rich pay shoots at Maldon, Bendigo, Steiglitz and elsewhere. It is usually associated with sulpharsenides and sulphantimonides but pyrite often accompanies it. A characteristic feature of the gold won from veins in which stibnite is the predominant sulphide is its high degree of fineness.

Chalcopyrite occurs widely spread in the reefs but usually is quite subordinate to the other sulphides. Bournonite is often prominent in the reefs of the Walhalla-Wood's Point belt but elsewhere is not abundant.

Mineral Associations.

The auriferous ores of Victoria may be classified according to the predominating ore minerals and their associations as follows:

1. Reefs in which stibnite is the chief ore mineral.

2. Reefs in which sulpharsenides and sulphantimonides are prominent.

3. Reefs in which pyrite and arsenopyrite predominate with lesser amounts of galena and sphalerite.

4. Reefs in which galena, sphalerite and pyrite are the most prominent ore minerals.

5. Ores containing abundant pyrrhotite and arsenopyrite.

6. Ores characterized by the presence of high temperature minerals.

1. *Stibnite.*—In reefs in which stibnite is the predominant ore mineral the following associations have been noted:

Rushworth and Whroo: Quartz, ankerite, stibnite, bournonite, tetrahedrite, pyrite and arsenopyrite with a little galena and sphalerite.

Alexandra and Diamond Creek: Quartz, carbonates, stibnite, arsenopyrite and pyrite.

2. *Sulpharsenides and Sulphantimonides.*—Reefs in which sulpharsenides and sulphantimonides are prominent are best known from the Walhalla-Wood's Point belt.

At the A.1. mine, Gaffney's Creek, the characteristic ore minerals are bournonite, arsenopyrite and pyrite with a little sphalerite. The gangue minerals are quartz and ankerite with minor quantities of albite and sericite. The gold from this mine is usually intimately admixed with the bournonite. At the Long Tunnel mine, Walhalla, bournonite, arsenopyrite, and pyrite are the chief ore minerals and quartz and ankerite the gangue minerals. At the Little Comet mine, Wood's Point, the vein minerals are quartz, ankerite, albite, arsenopyrite, tetrahedrite and pyrite. The gold is intimately associated with the arsenopyrite and tetrahedrite. Ulrich[24] records from the Albion reef, Steiglitz, quartz, stibnite, tetrahedrite, bournonite, pyrite and sphalerite. In addition ankerite, chlorite and arsenopyrite are fairly common in certain reefs at Steiglitz and albite and jamesonite have also been noted.

3. *Pyrite and Arsenopyrite.*—Reefs in which pyrite and arsenopyrite predominate with lesser amounts of galena and sphalerite occur in many important gold fields not directly associated with igneous rocks, as at Bendigo, Ballarat, Clunes, Daylesford, Castle-

[24] Ulrich, G., Contributions to the Mineralogy of Victoria, Melbourne, 1870.

maine, Scarsdale, Chiltern, and Harrietville. The following are typical associations of this class.

Bendigo: Quartz, carbonates (mainly ankerite), chlorite, pyrite, arsenopyrite, galena and sphalerite. Albite, sericite, pyrrhotite and stibnite occur in minor quantities.

Ballarat: Quartz, carbonates, albite, chlorite, pyrite, arsenopyrite, galena, and sphalerite. Pyrrhotite, chalcopyrite, boulangerite, and bournonite are rare constituents.

Daylesford: Quartz, ankerite, albite, chlorite, pyrite, and arsenopyrite. Galena, sphalerite, boulangerite, and jamesonite are less common but are often present in rich shoots.

Chiltern, Wandiligong and Harrietville: Quartz, carbonates, arsenopyrite, and pyrite with a little galena and sphalerite.

4. *Galena, Sphalerite and Pyrite.*—Reefs in which galena, sphalerite and pyrite are the most prominent ore minerals are exemplified in the Pyrenees belt between St. Arnaud and Avoca. In some cases the quartz is quite subordinate to the sulphides and locally the latter have been smelted for silver and lead. The gold recovered by amalgamation from these ores is invariably of poor quality and the sulphides are usually rich in silver. Typical associations of this class are as follows:

St. Arnaud: Quartz, galena, sphalerite, pyrite, and arsenopyrite. Carbonates are usually present and bournonite and chalcopyrite occur in minor quantities.

Redbank: Galena, sphalerite, pyrite and quartz, and occasionally bismuthinite.

Percydale: Galena, sphalerite, pyrite and quartz.

5. *Pyrrhotite and Arsenopyrite.*—Ores containing abundant pyrrhotite and arsenopyrite occur chiefly in metamorphosed older Paleozoic and Pre-Cambrian rocks, in the form of lenticular replacement deposits. They are usually highly mineralized and constitute refractory ores. The following associations have been met with:

Magdala lode, Stawell: Pyrite, pyrrhotite, quartz, carbonates, and chlorite. Arsenopyrite is uncommon.

Great Rand mine near Mansfield: Pyrite and pyrrhotite prevail. The gangue is a siliceous carbonate one. Small quantities of galena, sphalerite, arsenopyrite, and chalcopyrite are also present.

Bethanga: Arsenopyrite is the most common ore mineral; next, is chalcopyrite followed by pyrrhotite and pyrite with some galena, sphalerite, and stibnite.

Cassilis: As at Bethanga, arsenopyrite is the most abundant ore mineral. Pyrite, sphalerite, galena, and chalcopyrite with small quantities of bismuthinite and stibnite have also been noted.

6. *High Temperature Minerals.*—Ores characterized by the presence of high temperature minerals are confined to granitic rocks and their contact aureoles. The highly productive reefs of Maldon afford the best illustration. Quartz is the prevailing gangue mineral. Carbonates (chiefly ankerite) are next in order of importance. Felspar (albite ?), biotite, muscovite, chlorite, hornblende, garnet, apatite, and scheelite have also been recorded. The relatively low temperature minerals barite, opaline, silica, and the zeolites (chabazite and heulandite), strangely enough, occur in the same reefs. The predominant ore minerals are pyrite, arsenopyrite, pyrrhotite, and galena with lesser amounts of sphalerite, chalcopyrite and stibnite. Bismuthinite, native bismuth, maldonite, jamesonite, tetradymite, and molybdenite occur sparingly.

At Mt. William near Stawell the ores are in granodiorite. The gold is accompanied by molybdenite, pyrite, chalcopyrite, pyrrhotite, and scheelite (?).

Order of Deposition.

In general the gangue minerals were deposited before the gold and sulphides. Occasionally the carbonates are interlaminated with and veined by quartz but normally they are slightly later than both quartz and albite, which latter minerals are usually essentially contemporaneous. In most cases the gold is of late deposition and often it is the last mineral introduced. The following sequences of deposition have been observed in various fields:

Ballarat East: New Normanby and Last Chance mines. Quartz (earliest), albite, ankerite, sphalerite and galena, gold (latest).

The gold often coats the sphalerite and galena and occasionally crystals (usually rhombdodecahedra) of gold are seen on galena.

Gregory[25] gives the sequence of deposition in one specimen from the 997-foot level, Victoria United mine, as follows:

"The vein is mainly quartz traversed by veins of calcite; in these occur patches of galena, on the margin of which there are fine needles of stibnite. There is also some blende, with a deep yellowish red colour in thin sections. The blende occurs mostly on the margin of the galena. The free gold in this specimen is in the blende, as if they had been deposited together. On the edge of the galena is a little gold which was therefore deposited later than the galena."

Bendigo: The gangue minerals quartz, ankerite, and chlorite appear to be of earlier generation than the sulphides and the gold. Stillwell[26] contends that on the whole the last named minerals were deposited together and that one cannot be considered to have caused the precipitation of the others. Elsewhere[27] he says: "Occasionally cubes of pyrite and galena have been seen to be gilded with gold."

Daylesford on the 800-foot level, Ajax mine, the sequence is, quartz (earliest), albite, pyrite, and gold (latest). The gold encrusts and veins the pyrite and is disseminated through the albite and quartz. On the 800-foot level, Nuggety Ajax mine, are quartz, ankerite, pyrite, boulangerite and gold. The boulangerite and gold are intimately admixed and are essentially contemporaneous.

Walhalla-Wood's Point belt: The general order of deposition in this belt is as follows:[28]

[25] Gregory, J. W., The Ballarat East Gold Field. Mem. 4, Vic. Geol. Surv., 1907, p. 38.

[26] *Loc. cit.*, Bull. No. 4, 1917, p. 50.

[27] *Loc. cit.*, Bull. No. 16, p. 29, 1919.

[28] N. R. Junner, *loc. cit.*

Earliest formed, quartz, albite, carbonates, and pyrite, sphalerite, galena, arsenopyrite, bournonite, tetrahedrite and gold.

Latest formed, chalcopyrite and pyrite. The gold is intimately admixed with bournonite, arsenopyrite and occasionally tetrahedrita.

ORIGIN AND DEPOSITION OF THE GOLD.

Earlier Views.—Many of the earlier writers on Victorian geology believed that the gold existed in the sea water of early Paleozoic time; was deposited with the Ordovician and Silurian sediments and was later collected into the veins by the heat generated by granitic and other intrusions. This lateral secretion theory was apparently first advocated by Daintree[29] and was later accepted and supported in the whole or in modified form by various writers, including among others, the late Dr. A. W. Howitt, R. A. F. Murray, F. A. Rickard, E. Lidgey, and W. Bradford.

Thompson[30] dealing with the Wood's Point district where the reefs occur within dikes, also claimed that the mineral contents of the veins were derived from the rocks bounding them.

J. R. Don[31] showed that no gold existed in the sedimentary rocks away from the quartz veins and that a marked inverse ratio exists between the auriferous contents and the distance from the lodes. He concluded that the gold was not derived from the country wall rock but that it was deposited from heated ascending solutions.

In the Walhalla-Wood's Point belt and in numerous other places in Victoria, as at Dargo, Queenstown, Maryborough, and Granite Flat the auriferous reefs occur in or directly associated with igneous rocks rich in brown hornblende. To attempt to discover whether the iron magnesian minerals of these rocks

[29] Daintree, R., On the Age and Origin of Gold. Melbourne, 1866.

[30] Thompson, H. A., The Formation of Mineral Veins and the Deposits of Metallic Ores in Them. *Trans. Roy. Soc. Vic.*, vol. 8, p. 268, 1868.

[31] The Genesis of Certain Auriferous Lodes. *Trans. Amer. Inst. Min. Eng.*, vol. XXVII, pp. 610–656, 1898.

were the source of the precious metals, as has been suggested by various writers for similar occurrences in other countries,[32] Don[33] made comprehensive assays of

1. Cohen's dike, Walhalla, containing no sulphides and not associated with an auriferous quartz reef.

2. Cohen's dike associated with such reefs.

3. Hornblende separated from Cohen's dike and the Thomson River copper mine dike.

His results indicated that when no quartz was associated with Cohen's dike the rock contained little or no sulphides and was not auriferous; that where the dike was associated with quartz, but the quartz was auriferous, the dikes was likewise barren; that the percentage of sulphides in the dike was greatly increased when it was associated with highly pyritiferous quartz and then the dike sulphides are auriferous, though much less so than those of the associated reefs; and that no trace of gold was present in the hornblende.

The following assays of propylitized and vein altered dike rocks from the vicinity of Wood's Point and Gaffney's Creek were made for me by Mr. H. R. Murphy of the School of Mines, Ballarat.

No. 24.—Propylitized mica hornblende lamprophyre, A. 1. mine, Gaffney's Creek.	No gold detected.
No. 7.—Vein altered dike containing a little pyrite—No. 9. Intermediate level, A. 1. mine.	No gold detected.
No. 67.—Propylitized diorite porphyrite, 400-foot level, Morning Star mine, Wood's Point.	No gold detected.
No. 46.—Hydrothermally altered diorite porphyrite containing much pyrite, from close to a quartz vein, Hope adit level, Morning Star mine.	3.5 grains of gold per ton.
No. 135—Vein altered dike containing very little pyrite—Hunt's mine, Gaffney's Creek.	No gold detected.

[32] G. F. Becker, Geology of the Comstock Lode. U. S. Geol. Surv., Mon. 3, p. 223, 1882.—B. Von Inkey, De la Relation entre l'état Propylitique des Roches Andesitiques et leurs Filons Mineraux. Internat. Geol. Congress, Mexico, 1906.—C. G. Gibson, The Geology and Ore Deposits of Calgoorie: East Coolgardie Goldfield, Bull. 42, West Austral. Geol. Surv., part 1, p. 29.

[33] *Idem.*

These results suggest that there is no gold inherent in the propylitized rocks away from the quartz veins and that gold is only present in the vein altered types when pyrite is present in fair amount. In conclusion, Dr. Don's results effectively dispose of the lateral secretion theory both for reefs within and associated with igneous rocks and those in sedimentary rocks.

In 1861, Belt[34] claimed that the auriferous quartz reefs of Victoria were formed as igneous intrusions and that they represented the extremely acid final stage of some quartz felspar dikes of which all the felspathic material had been removed by its crystallization and retention in some lower zone. As Gregory[35] points out, Belt thus anticipated certain modern petrographic conclusions.

Ulrich, in the early sixties, observed the close association of the auriferous reefs with igneous rocks and further noted that in Gippsland the reefs frequently increased in richness as they approached the dikes. At Maldon adjoining the Mount Tarrengowen granodiorite massif Ulrich[36] claimed that certain granite apophyses passed directly into auriferous quartz reefs.

Origin of Gold.—Briefly summarized, the evidence in support of a magmatic origin of the gold-bearing solutions is as follows:

1. An outstanding feature of the auriferous ores in Victoria is their constant proximity to igneous rocks of approximately contemporaneous age. Bendigo and Daylesford are the chief exceptions. Granodiorite outcrops about eight miles south of Bendigo, and Stillwell[37] has traced a connection between this intrusion and the auriferous reefs of Bendigo. In the Daylesford area the extensive flows of newer basalt of Pliocene (?) age may have covered up any older igneous rocks.

2. Auriferous pegmatites are known from Linton's, Huon's

[34] Belt, T., Mineral Veins: and Inquiry into their Origin, Founded on a Study of the Auriferous Quartz Veins of Australia, pp. 21–22, 1861; quoted by J. W. Gregory. See note 35 below.

[35] The Ballarat East Gold Field. Mem., Geol. Surv. Vic., 4, 1907, p. 43.

[36] Ulrich, G., Observations on the Nuggety Reef at Mt. Tarrengower Gold Field, *Q. J. G. S.*, London, vol. XXV, 1869, p. 326.

[37] *Loc. cit.*, Bull. No. 16, 1919, p. 9.

Lane near Wodonga, and Maldon. At the last named place Ulrich observed the direct passage of granite apophyses into auriferous quartz reefs.

3. Viewed broadly there is often a zonal change in the mineralogical character of the reefs dependent on their distance from granitic intrusions. At Mt. William, Maldon, Bethanga, and Stawell where the reefs occur within and adjoining such rocks, high temperature minerals such as molybdenite, pyrrhotite, arsenopyrite, garnet, and biotite are present, while in reefs further removed these minerals are absent or present in small quantities and galena, sphalerite, stibnite and pyrite are more prominent.

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4. In the Walhalla-Wood's Point gold belt where the ores are intimately associated with dike rocks which range in composition from granophyre and quartz porphyry to peridotite, the richest auriferous reefs are connected with rocks of dioritic and gabbroidal composition—diorite and gabbro porphyrites, and lamprophyres—and reefs connected with more acid and more basic types have yielded little gold. This suggests that the origin of the gold is connected with the differentiation of the igneous rocks of this belt.

5. Field and petrological examinations show that in all cases the ore and gangue minerals have been deposited in the veins from solutions. That these solutions were ascending thermal ones is clearly proved by the nature of the vein minerals and the character of the wall rock alteration. In most cases the vein waters appear to have been siliceous and alkaline carbonate ones, containing, in addition, sulphur and arsenic and often small quantities of antimony, bismuth, iron, copper, lead, and zinc. The waters of hot springs in areas of expiring volcanism often contain quantities of alkaline carbonates, sulphides, silica, and much smaller amounts of the rarer elements including gold, silver, copper, zinc, lead, arsenic, antimony, and mercury; and the gases emitted from volcanoes[38] sometimes contain important quantities of water, carbon dioxide, sulphur dioxide, and sulphur. The

[38] E. S. Shepherd, The Composition of the Gases of Kilauea, *Bull. Hawaiian Volcano. Obs.*, vol. 7, pp. 94–97, 1919.

writer believes that both gases and waters of this nature are of magmatic origin.

In conclusion, all the available evidence supports the theory that the gold primarily came from magmatic sources and no theory of lateral secretion or deposition from meteoric waters can explain all the facts of the occurrences of the gold.

Deposition of the Gold.—The main deposition of primary gold in the reefs appears to have been due to the precipitating influence of the wall rock and included fragments of it in the reefs and previously formed vein minerals. Stillwell[39] considers carbonaceous matter to have been the chief precipitating agency of the gold in the Bendigo reefs but believes also that the vein carbonates and sulphides have assisted its precipitation. At Wood's Point and Gaffney's Creek, arsenopyrite, pyrite, and carbonates have played an important part in precipitating the gold and in some cases carbonated dike fragments in the wall rock have had the same effect. At Ballarat East, crystals of galena and sphalerite partially coated with gold were not uncommon in some mines, and large masses of gold were sometimes found where thin carbonaceous and pyritic seams intersected the reefs.

At Ballarat West[40] the pay shoots of ore occur within certain beds of black carbonaceous slate and the bulk of the gold in the reefs is deposited on the pyritized films of the wall rock slate. At Daylesford and also at Bendigo brecciated slate fragments are sometimes lined or encrusted with gold. Elsewhere in Victoria carbonaceous matter in the reefs and in the adjoining wall rocks generally has a beneficial effect on the gold values.

In all these cases, with the possible exception of Ballarat East, the solutions that introduced the gold were undoubtedly alkaline carbonate and sulphide ones, yet we have clear evidence of the precipitation of the gold by carbonaceous matter, pyrite, and other reducing agents which evidence appears to conflict with the ex-

[39] *Op. cit.*, 1919, p. 29.

[40] H. Herman, Economic Geology and Mineral Resources of Victoria, Bull. 34, Vic. Geol. Surv., 1914, p. 15.

perimental results of Lenher[41] who says: "The sulphide solutions of gold are permanent stable solutions to the ordinary reducing agents, that is, to such reducing agents as precipitate gold from the chloride solutions."

SUPERFICIAL ORES.

As is usual in most countries the superficial oxidized ores in Victoria were on the whole much richer than the primary sulphide ores below. In fact, in many districts, including among others Tarnagulla, Rheola, Dunolly, Wedderburn, Inglewood, and the Pyrenees and Wood's Point belts, the majority of the reefs, although often rich and productive in the oxidized zone, became poor and unpayable in the primary sulphide zone. The following are conspicuous examples—by no means comprehensive—of marked superficial enrichment.

The Poverty reef at Tarnagulla yielded nearly £1,500,000 ($6,290,000) of gold to a depth of 350 feet from ore averaging several ounces to the ton. Below this depth the reef was poor. At 550 feet the quartz averaged about 10 dwts of gold per ton and little of it was considered payable and at 900 feet two reefs were cut—one 4 feet wide and the other 8 feet wide—but both were unpayable.

From the Morning Star dike at Wood's Point more than £1,000,000 ($4,860,000) of gold was obtained from the surface to a depth of 400 feet. Below that depth considerable prospecting has been carried out but very little payable gold has been discovered. In the same district the Royal Standard mine yielded considerably more than £50,000 ($243,000) of gold from about 7,000 tons of ore to a depth of 70 feet, but below that depth little if any payable ore was found. The first crushing from this mine yielded 2,934 ounces gold from 300 tons of ore. Other examples of marked superficial enrichment are common in the Walhalla-Wood's Point belt.

[41] Lehner, Victor, Transportation and Deposition of Gold in Nature, ECON. GEOL., vol. 7, 1912, p. 747.

At Bendigo the richest quartz in almost every case was obtained near the surface. Whitelaw[42] quotes statistics which illustrate the extreme richness of the reefs in the Confidence group of mines near the surface. The first recorded crushing by Taylor and Lindsay yielded 3,035 ounces of gold from 3 tons of quartz and several other crushings that followed returned 700 ounces to the ton. Thorpe's party crushed one ton of quartz for 800 ounces of gold and from an adjoining claim 2,500 ounces of gold were won from 5 tons of quartz. The Cinderella mine to a depth of 396 feet yielded a profit of £180,000 ($874,800).

At Maldon many of the reefs were very rich near the surface but failed to maintain their values in depth. The reef at the Beehive mine for instance went 200 to 300 ounces to the ton at a depth of 20 feet and yielded approximately £103,300 ($502,-038), gold from surface to a depth of 300 feet, but at a depth of 600 feet became unpayable. One claim, 39¼ feet long, on the Nuggety reef, Maldon[43] yielded 45,000 ounces of gold to a depth of 280 feet. At 280 feet the yield fell off considerably and was poor at a depth of 420 feet.

Such enrichments as have been described are due to either one or a combination of the following causes.

1. The gold from the former upward extensions of the reef being mechanically concentrated "in situ," at or close to the outcrops of the reefs.

2. The gold being concentrated in the oxidized zone by removal in solution of the valueless ore and gangue minerals.

3. The gold being concentrated in the oxidized zone particularly in the vicinity of the water level by downward migration of the gold in solution.

Rich outcrop ores were characteristic of many important fields in Victoria as Bendigo, Castlemaine, Maldon, Stawell and in the Walhalla-Wood's Point belt. In all these places the first crush-

[42] Whitelaw, H. S., The Confidence Group of Mines, Bendigo, Bull. Vic. Geol. Surv., 1918, p. 7.

[43] Brough Smyth, The Gold Fields and Mineral Districts of Victoria, 1869, p. 313.

ings were frequently much richer than any that followed. Much of the gold was loose and in certain cases as at Morning Star Wood's Point, it paid to sluice the soft decomposed outcrops of the ores. Cases of marked enrichment due to reduction in volume by the leaching of the valueless ore and gangue minerals are exceptional. In general the ores contain less than 2 per cent. of sulphides and quartz normally forms 90 per cent. of the gangue minerals.

There is distinct evidence in many districts of downward migration of the gold in solution causing, in certain cases, important enrichments. In general such migration of the gold is not extensive owing to the small amounts of iron sulphides in the reefs; the presence of neutralizing agents such as carbonates; and the constant presence of precipitants such as carbonaceous matter, carbonates and sulphides. According to Emmons[44] the materials whose presence is favorable, if not essential, for gold enrichment by solution are (1) chloride solutions, (2) iron sulphides, (3) manganese compounds. Iron sulphides are almost invariably present in small amounts. Chlorides have been found in all mine waters tested and certain ones such as those of Bendigo, St. Arnaud and Maldon were relatively rich in chlorides. Manganese oxides are most prominent in ores associated with igneous rocks of intermediate to basic composition, *e.g.*, in the Walhalla-Wood's Point belt, Maryborough and in the Pyrenees belt. In these cases it is derived from the ferromagnesian silicates and from the vein carbonates. At Ballarat, Bendigo, Daylesford, and elsewhere where the ores occur in sedimentary rocks the vein carbonates are manganiferous but in general the sediments appear to contain very little manganese.

Examples of Migration of Gold in Solution.—At St. Arnaud, the primary ore is highly mineralized quartz carrying in places up to 25 per cent. or more of sulphides, mainly argentiferous galena, pyrite, arsenopyrite, and sphalerite. Close to the surface finely divided gold occurred associated with hydrated manganese iron

[44] Emmons, W. H., The Enrichment of Ore Deposits, Bull. 625, U. S. Geol. Surv., 1917, p. 323.

oxide, and cellular quartz. This ore was low in silver. From about 100 feet to 200 feet veinlets of secondary silver minerals—chiefly embolite—associated with finely divided gold, cerussite, azurite, malachite and limonite became prominent. Below 200 feet the primary ore was encountered. The gold values in general were richest at and near the surface. The following figures suggest a downward migration of the gold. The Western reef at a depth of 100 feet and for some distance higher gave 1 to 1½ dwts. of gold per ton; at 150 feet, 5 dwts.; at 200 feet, 8 dwts.; and then downward to 230 feet, 9 dwts. per ton.

Shewring's reef from the surface to 50 feet averaged 1 to 1¼ ounces of gold per ton; from 50 to 110 feet, 3 ounces to the ton; from 110 to 140 feet, 6 to 7 ounces per ton, and from 140 to 170 feet about 12 dwts. per ton.

Of considerable interest are the pockets of rich secondary gold associated with certain dikes in the Walhalla-Wood's Point belt.[45] At the Geogia mine, Enoch's Point, the gold is associated with a narrow lamprophyre dike which cuts across easterly dipping Silurian shales and sandstones. Small veins of quartz, 2 to 3 inches in width, occur as flat "floors" within the dike but have proved barely payable. Rich patches of nuggety and fine gold practically free from quartz and often coated with arsenopyrite and hydrated oxide of manganese are found on ledges or shoulders of hard sandstone on the hanging wall of the dike. These ledges are formed by rolls in the dike or by small displacements as in figure No. 3. Nuggets of gold up to 36 ounces in weight have been extracted from these pockets. Nuggety gold is absent from the veins within the dike. Some of the coarse gold is intimately admixed with calcite. Most of the fine gold is loose and free from quartz and occurs in well crystallized fern like growths coated frequently with psilomelane and arsenopyrite. Botryoidal aggregates and crystals of gold deposited on arsenopyrite have also been found in these pockets. The source of the manganese probably lies in the dike and the vein carbonates.

[45] Junner, N. R., *loc. cit.*, 1920.

At the May Moon dike near Matlock, according to Whitelaw,[46] "The greater part of the gold is obtained not in quartz leaders traversing the dike but in a brown clay or 'dig' which lies between the contact of the dike and the sedimentary beds. The gold is said to be very often associated from quartz."

One nugget weighing upwards of 100 ounces was obtained from one of these patches at a depth of about 200 feet.

The accompanying recorded yields of the A.1. mine, Gaffney's Creek, from 1862 to 1892 show an important enrichment—probably due to downward migration of the gold—at depths between 100 and 180 feet.

Depth.			Ozs. per Ton.
0– 50'.....	5,652 tons	7,747 ozs.	1.37
60'– 40'.....	7,991 tons	10,962 ozs.	1.38
100'–130'.....	10,567 tons	20,511 ozs.	1.94
150'–180'.....	3,871 tons	6,626 ozs.	1.71
200'.....	1,505 tons	1,267 ozs.	0.84
250'.....	120 tons	48 ozs.	0.40

The majority of the pocket deposits of so-called "indicator" occurrences of Ballarat East, Wedderburn, Dunolly, Moliagul, Rheola, Tarnagulla, and Maryborough appear to be of secondary origin. Much of the gold from these deposits was in coarse nuggety form. On all the above mentioned fields with the exception of Ballarat the pockets were most abundant above 200 feet from the surface and below 400 feet they were of exceptional occurrence. The fineness of the gold from these deposits is characteristically high and in some cases much greater than that won from deeper mines in the same locality. The following are favored places for finding these pockets..

1. At the intersection of quartz veins with bedded pyritic and carbonaceous seams—Ballarat East, Maryborough and Daylesford.

2. At the intersection of relatively flat and steeply dipping quartz veins—Queenstown, Wedderburn, Little Comet mine Wood's Point, etc.

[46] Whitelaw, O. A. W., The Wood's Point Gold Field, Mem. 3, Vic. Geol. Surv., 1905, p. 26.

3. In the vicinity of the intersections of quartz veins (usually flat dipping) with faults and small fissures—Rheola, Moliagul, Ballarat East, Birthday Tunnel, Berringa, etc.

4. On ledges or shoulders formed by local changes in the dips of reefs—near Wood's Point, Rushworth and Wedderburn.

The type indicator field is that of Ballarat East. Diverse views have been expressed as to the nature of the indicators on this field. Krause, Lidgey, Rickard and others regarded them as thin beds of black carbonaceous slate containing much pyrite. Gregory and Bradford on the other hand believed them to be secondary structures which crossed the bedding planes irregularly. Recently, Baragwanath[47] has shown conclusively that the indicators are essentially bedded. He has traced them at the 1,204 feet level at the Woah Hawp Canton mine around two anticlines and an intervening syncline.

Gregory[48] claims that the indicators are chiefly thin chloritic bands but that some of them are thin seams of pyrite. His contention that the black color of the slates is due to rutile is not generally accepted. Some of them are undoubtedly rich in carbonaceous matter. At places along the intersection of these indicators with the reefs which cross them and particularly in the vicinity of faults and minute cross fissures termed "heads" rich pockets of gold—"Sometimes in slugs weighing several hundreds of ounces"[49] are found. Altogether about 70 such nuggets of 50 ounces or above in weight have been recorded from Ballarat East. They were found at all depths from the surface to 1,300 feet.

The evidence in support of the theory that the bulk of the gold in the pockets has been deposited from downward moving meteoric waters, briefly, is as follows:

1. A characteristic feature of the Ballarat East gold field is the extensive faulting and fracturing later than the formation of the reefs. Much of this faulting probably took place in late

[47] The Ballarat Gold Field, Mem., Vic. Geol. Surv. (in press).
[48] *Loc. cit.*, p. 13.
[49] H. Herman, *loc. cit.*, p. 13.

Tertiary or Pleistocene time accompanying the near-by volcanic activity. Of the 70 nuggets upwards of 50 ounces in weight recorded from Ballarat East nearly 50 of them came from two adjoining mines, namely the North Woah Hawp and the Woah Hawp Canton. It is perhaps significant that these mines were exceptional for the number of faults of later age than the reef formation.

2. At the North Woah Hawp mine masses of kaolin were found in the reefs at depths as great as 1,200 feet. Hydrated manganese and iron oxides have not been noted in the reefs at depths greater than 400 or 500 feet but marcasite is sometimes present in depth.

3. A study of the paragenetic relations of the vein minerals shows that in nearly all cases the gold was the last mineral introduced. It often occurs deposited on galena and sphalerite and less commonly on pyrite and pyrrhotite, and sometimes filling fractures in friable quartz.

4. Gregory[50] has pointed out the very high degree of fineness of the Ballarat East gold and has suggested that most of the gold has been deposited from descending waters. According to him[51] the average fineness of the gold from the deeper Ballarat East mines is about 974, and that of the Exchange mine, 995.5.

Next to Ballarat the indicator occurrences of Maryborough and Wedderburn have received most study. At Maryborough the indicator is usually a thin bedded laminated quartz vein within a bed of green or purple pyritic slate. According to Howitt[52] gold never occurs in the indicators. Psilomelane was common at the surface along many of the richer reefs. Practically all the gold from these indicator patches came from above water level.

At Wedderburn—a field characterized by nuggety placer deposits—rich pockets of nuggety gold have been found above water level in several mines along the intersections of indicators

[50] *Loc. cit.*, p. 44.

[51] *Loc. cit.*, p. 44.

[52] Howett, A. M., The Maryborough Gold Field. Mem., Vic. Geol. Surv. No. 11, 1913. The above notes are in the main extracts from this memoir.

with relatively flat quartz veins as in Fig. 15. The indicators are usually thin bedded iron stained quartz veins within beds of carbonaceous slate. In his memoir on this area Whitelaw[53] states, "I have not noticed one instance of an indicator producing rich pockets of gold where this metasomatic quartz is absent." He also claims that the gold-bearing solutions circulated in the fault planes and in the indicators themselves and quotes analyses

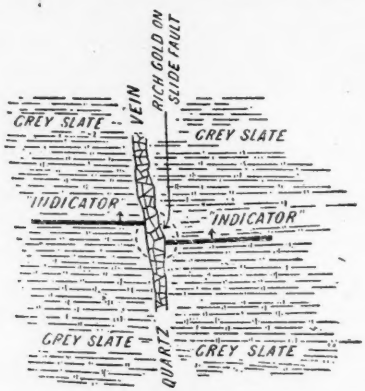

FIG. 15. Sketch section of indicator, Shaw's reef, Wedderburn. (After Whitelaw.)

showing that the indicators are always auriferous. He[54] suggests a secondary origin for a portion of the gold in these pockets. Manganese oxides are not mentioned.

Summary.—Generally speaking rich placer and enriched outcrop ores are characteristic of Victoria. This is particularly true of the Western portion of the colony where the ores occur mainly in sedimentary rocks which contain abundant precipitants of gold from chloride solutions, and on the whole are poor in manganese. In general no extensive downward migration of the gold in solution has taken place in these districts. Ballarat is a

[53] Whitelaw, D. A. L., The Wedderburn Gold Field, Mem., 10, Vic. Geol. Surv., 1911, p. 13.

[54] *Idem*, p. 20.

possible exception. In Eastern Victoria where the ores are often directly associated with igneous rocks, examples of enrichment due to solution of the gold and its redeposition at lower levels are not uncommon but they are rarely of any magnitude. The deposition of gold nuggets from descending surface auriferous waters has been clearly established near Wood's Point and Enoch's Point in Eastern Victoria and the writer is of the opinion that much of the nuggety gold of the indicator occurrences of Western Victoria has been formed in a similar manner.

PLACER DEPOSITS.

General.

The auriferous placer deposits of Victoria for productivity and richness rank with those of California as the foremost in the world. According to Herman[55] the total value of gold won from alluvial mining in Victoria is probably not less than £150,000,000 ($729,000,000).

Naturally, the earliest worked deposits were those exposed at the surface, such as the gravels in the beds and on the flanks of the valleys of modern and fossil rivers, and certain widespread sands and gravels capping hills. Deposits of this kind at Ballarat, Bendigo, Castlemaine, Rheola, and elsewhere yielded vast quantities of nuggety and fine gold in the early mining days. About 1855 it was discovered at Ballarat that certain auriferous gravels continued underneath the basalt. This led to the development of the so-called "Deep Lead" deposits which proved so rich and highly productive at Ballarat West, the Loddon Valley and elsewhere.

For many years the yield of gold from placer deposits exceeded that from quartz reefs but at the present time alluvial mining is at a very low ebb and the bulk of such gold is being won by dredging and sluicing.

The average fineness of the placer gold is almost invariably greater than that of the primary reef gold from the same district.

[55] *Op. cit.*, p. 28.

The explanation is not far to seek. Placer gold is derived almost entirely from the oxidized zones of the reefs and Don[56] has shown that the average fineness of the gold in the vadose zone on various Australian fields is appreciably greater than that in the deeper levels of the same district. Some refining of the gold may have taken place after the placers were formed but only in a very minor degree.

Classification and General Description.

The auriferous placer deposits of Victoria may be conveniently classified as follows:

Pre-Older Basaltic Deposits.
- Sub basaltic deep leads.
- High level gravels of Western Victoria.

Pre-Younger Basaltic Deposits.
- Sub newer basaltic deep leads.
- Deep leads buried beneath beds of sand and clay.
- Buried coastal gravels.

Post-Younger Basaltic Deposits.

Pre-Older Basaltic Deposits.—**Sub Basaltic Deep Leads.**—Elevated remnants of ancient river-gravels occur in many places in Eastern Victoria buried in practically all cases by lavas of older basaltic age. In places they are found at elevations exceeding 5,000 feet above sea level and upwards of 2,000 feet above the beds of present-day streams. In general the deposits are very quartzose consisting of quartz gravels and sands, siliceous and ferruginous conglomerates, and quartzite. Overlying these gravels and underlying the older basalt in many places are beds of sand, clay and impure lignite indicating swampy and probably gradually sinking conditions. Almost without exception these deposits have proved auriferous but in no case have they yielded amounts of gold comparable with that won from the leads of Western Victoria. The gold is usually fine and well rounded and more uniformly distributed than in the sub newer basaltic places.

[56] *Op. cit.*, p. 607–608.

High Level Gravels of Western Victoria.—These are so called since in general they cap and flank hills and ridges above the general level of the present-day streams, and the sub younger basaltic deep leads. At Ballarat West, however, they are covered up by newer basalt and are in part below the level of the present-day streams although above the general level of the deep leads.

Remnants of sheets of flat-bedded sands and gravels of this nature are widespread in Western Victoria. Locally they have considerable areal extent and rarely do they appear to have been formed in the beds of river valleys. They have been regarded as of marine origin but without sufficient evidence. It is more probable that they are mainly lacustrine or flood plain deposits. Their pre-older basaltic age has not been established. They are certainly older than the sub younger basaltic deep leads and may possibly be contemporaneous with the marine transgression in Miocene (?) time.

These deposits are auriferous in practically all cases but the gold is usually fine and rounded and fairly uniformly distributed through them. Only in isolated cases have they proved richly auriferous.

Pre-Younger Basaltic Deposits.—**Sub Younger Basaltic Deep Leads.**—Auriferous river gravels from which probably not less than £50,000,000 ($243,000,000) of gold has been unearthed, immediately underlie the younger basalt of Western Victoria in many places. The deep leads of Ballarat and the Loddon Valley are most famous. Those of Ballarat are reported to have yielded approximately £7,000,000 ($34,020,000) of gold and those of the Loddon Valley not less than £15,000,000 ($72,900,000).

In general the level of these leads is below that of the present streams but at Daylesford the reverse is true. The work of the Geological Survey has demonstrated that the directions of these ancient rivers and the position of the pre younger basaltic main divide were very similar to the present ones. The auriferous wash is usually fairly coarse and normally is overlain by finer

gravels, sands, and clays. The composition of the wash differs somewhat from that of the sub older basaltic deep leads; there is a much greater proportion of pebbles in the former. The gold also is much coarser and less rounded, on the whole, and the bulk of it is traceable to nearby reefs. Marked enrichment of the leads has been noted in certain places, as at Ballarat West, where the leads cross auriferous reefs.

Deep Leads Beneath Beds of Clay and Sand.—The best known and richest deposits of this type are the deep leads of the Chiltern and Rutherglen districts and those of the Avoca Valley, Ballarat East, Stawell, Dunolly, and Tarnagulla. Others of a similar nature have been worked with various degrees of success northwest of Bendigo, Beaufort, Landsborough, Alexandra and elsewhere. The auriferous gravels occur at all depths from a few feet to 350 feet or more below the surface. In the Rutherglen-Chiltern area they occur at depths as great as 350 feet; in the Avoca Valley at an average depth of about 200 feet; at Stawell 45 to 100 feet deep; Beaufort 110 feet and Dunolly, 20 to 60 feet. In general the overburden is mainly variegated clays with intercalated thin beds of sand and gravel. Near Stawell the leads pass into Marine sediments and it is probable that the silting up of most of these valleys occurred contemporaneous with the great marine transgression in Miocene (?) time. In general the bulk of the gold in the leads is of fairly local origin and can be traced to nearby reefs. The deep leads of Ballarat, Tarnagulla and Dunolly were famous for the number and size of the nuggets found in them.

Buried Coastal Gravels.—Auriferous places of this kind are known at Pitfield, Rokewood, and near Stawell. At the first named places they are buried beneath a considerable thickness of younger basalt while near Stawell they are covered by beds of clay, sand, and cement (ferruginous conglomerate). The present elevation of these gravels at Pitfield is about 370 feet above sea level.

Post Younger Basaltic Placers.—The great uplift in Victoria

in late Tertiary time continued after the burying of the ancient rivers by the younger basaltic lavas. It resulted in rapid erosion of the upper enriched zones of the reefs and previously formed placer deposits, and the accumulation of rich placers in the beds and on the sides of the valleys of recent and present-day streams. In the early mining days extremely rich deposits of this nature—many of them rich in nuggety gold—were worked at Bendigo, Ballarat, Castlemaine, Wedderburn, Maryborough, Rheola, and elsewhere.

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RELATIONS OF TEXTURE AND BEDDING TO THE MOVEMENTS OF OIL AND WATER THROUGH SANDS.[1]

R. VAN A. MILLS.

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INTRODUCTION.

It is a matter of common knowledge that the recovery of gases, oils, and waters from their reservoir rocks depends directly upon the deep-seated movements and rearrangements that the fluids undergo incident to the drilling and operation of wells. Under various conditions, the movements of the fluids are differential, one fluid or another tending to advance ahead of the others. This is exemplified in the field by the comparatively rapid escape of gas with consequent lowering of "rock pressure" before the recoverable oil is exhausted; and also by wells or entire fields going to water before the recoverable oil is exhausted. Experimental data tending to establish some of the factors and relationships governing induced movements and rearrangements of gas, oil, and water, in their reservoir rocks, have been previously published.[2] The purpose of this paper is to present further experimental evidence that both the natural and induced movements and rearrangements of oil and water in

[1] This is the second paper in a series of preliminary contributions describing experiments that the writer is pursuing for the United States Bureau of Mines. The Introductory paper was "Experimental Studies of Subsurface Relationships in Oil and Gas Fields," ECON. GEOL., vol. 15, p. 398, 1920.

[2] *Idem.*

sands are governed largely by the textures and bedding, and more especially by variations of these conditions in the reservoir rocks.

The writer points out that he has used the term "induced" to differentiate the deep-seated effects caused by drilling and operating wells, from the effects of natural processes prior to drilling. Thus the movements and rearrangements of gas, oil, and water incident to the drilling and operation of wells are termed "induced movements and rearrangements." There is a wide variation of *induced effects* in oil and gas fields involving migration and rearrangements of the gases, oils, and waters, together with physical and chemical changes in both the fluids and the reservoir rocks.[3] Field and laboratory studies of these induced effects throw important light upon the natural processes of oil and gas migration and accumulation as well as upon problems of underground recovery.

EXPERIMENTAL APPARATUS.

The apparatus developed for this type of experimental work has been previously described.[4] It consists essentially of rectangular steel tanks with removable top and front plates and with openings and cocks arranged as shown by Fig. 16. The front plates are glass to facilitate making observations and photographic records of experiments. The internal dimensions are 92 by 48 by 9 cm., or 36.22 by 18.90 by 3.51 inches. Two of these tanks were used for the experiments herein described.

CONDITIONS OF EXPERIMENTATION.

The difficulty of reproducing underground conditions in the laboratory has led to the development of comparative methods of study through which some of the broad principles and relationships governing the occurrence and recovery of oil and gas are studied. Comparisons are made in the laboratory between the behaviors of oils, gases, and waters in different kinds of

[3] See U. S. Geol. Survey Bulletin 693.

[4] *Loc. cit.*

sands, under different sets of conditions. The point is emphasized that the purpose of the experiments is to study the effects of differences between various underground conditions rather than to reproduce underground conditions in the laboratory. The differences between the various sets of experimental conditions in the laboratory are of the same order, though not of the same magnitude as the differences between the underground conditions in the field. It follows, therefore, that many of the prin-

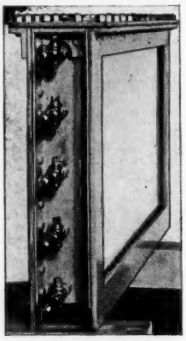


FIG. 16. End view of Experimental Apparatus.

ciples and relationships revealed through this type of comparative study are identical with those governing the occurrence and recovery of oil and gas.

The methods of preparing and conducting the experiments were outlined in the introductory contribution.[5] They are also briefly described in the succeeding pages of this contribution. Throughout the experiments herein described, the variations in the conditions of experimentation were limited principally to differences in the textures and bedding in the sands and the modes of introducing and extracting oil and water from the sands. The propulsive force was exerted by hydrostatic pressure. Similar experiments in which the propulsive force was

[5] *Loc. cit.*

exerted by expanding gas will be described in a later contribution. Experiments involving variations in temperature will also be described in other contributions. The temperature of experimentation was 70° F. (21.1° C.) and the pressures were less than five pounds per square inch.

MATERIALS USED.

The sands used in the experiments are recorded in Table I. The oil was black Appalachian "crude" with a specific gravity of 0.824 (39.9° B.) at 60° F. (15.6° C.) and Engler viscosity of 1.573. At the temperature of experimentation (70° F.) the specific gravity of the oil was 0.820. Only one quality of water, a chloride brine having a specific gravity of 1.100 was used. The cap sand, in each experiment, was wet with the water before being packed into place.

TABLE I.

SANDS USED FOR EXPERIMENTATION.[a]

Marks Designating Sands in Photos.	Ranges in Diam. of Grains (Millimeters).[b]		Total Porosities Expressed as Percentages of the Volumes of the Sands.[c]
a	6.350	1.651	36
b	0.833	0.589	38
c	0.417	0.074	37
d	1.168	0.833	37
e	0.589	0.074	38
f	6.350	0.833	37
g	6.350	1.168	36
h	0.295	0.074	40
i	0.295	0.074	36
j	0.833	0.074	35

[a] These are white quartz beach sands with rounded and partly rounded grains, except *c*, which is a fine, sandy material from drill sludge.

[b] Screen analyses of these sands will be presented in later papers.

[c] Averages from five tests upon each sand, expressed to the nearest per cent.

PHOTOGRAPHIC RECORDS.

The photographs reproduced in Plates III. to VI. are selected from a large number of progress pictures illustrating various stages of each experiment. The sands are designated in the photographs by letters corresponding with those used in Table I.

EXPERIMENTS.

Experiment 1 illustrates the relations that certain variations in the textures and bedding of pay sands bear to the induced movements of oils of low viscosity and water, more especially to the forming of water-cones during the recovery of oil and water through wells. The bedding of the sands in both tanks was horizontal, but the upper part of the pay sand in tank 1 was relatively fine, whereas the upper part of the "pay" in tank 2 was relatively coarse. The oil and a part of the water in each tank were introduced with the sands as they were packed into place. Air was also included in the sands as finely disseminated bubbles and as absorbed gas in the oil and water. The sands were further saturated and the oil raised against the water-wet cap sand *c* by introducing more water through the bottoms of the tanks after the cover plates were attached. The air displaced during the procedure was allowed to escape through the wells. The fluids were then allowed to adjust themselves under hydrostatic conditions for 24 hours, during which time part of the included air segregated and accumulated above the oil, against the cap sand *c*, according to the underlying principles of the anticlinal theory. The wells consisted of 3/8 inch pipes situated 4.5 centimeters inside of the plate glass fronts of the tanks and extending one centimeter below the tops of the pay sands. Plate III., *A* and *B*, show the arrangements of the fluids before extraction through the wells had commenced.

Plate III., *C* and *D*, show the arrangements of the fluids twenty minutes after extraction through the wells had commenced. The propulsive force was exerted by the pressure (3-foot head) of the water, which was admitted at the ends of the tanks as indicated by the arrows. The air overlying the oil had escaped through the wells. In tank 1, the water flowing through the coarse sand *g* advanced ahead of the oil and entered the fine sand *d*, producing a water cone and rendering the fine sand around the well more permeable to water but less permeable to oil. The effect was to retard the movement of the remaining oil to the well. In contrast to this, the oil with its included air in tank 2 under-

went induced migration and segregation from the fine into the overlying coarse sand to replace the oil being extracted. There was no apparent water cone, nor was any appreciable amount of water extracted through the well in tank 2 during the initial twenty minute period of extraction.

Plate III., *E* and *F*, show advanced stages of water coning in both tanks forty minutes after extraction commenced. In tank 1, the differential movements of the oil and water causing the water coning were accentuated by the water flowing through the coarse sand *g* to the vicinity of the well and then cutting upward through the fine sand ahead of the remaining oil. As the water, together with a decreasing proportion of oil, continued to flow to the well, the water cone was enlarged so that the sand around the well became increasingly permeable to water but decreasingly permeable to oil. The oil remaining in the relatively fine sand *d* was practically excluded from the well.

The movements and rearrangements of the fluids in tank 2 afforded a striking contrast to those in tank 1. The water upon entering the fine sand *d* in tank 2 flowed upward into the coarse sand *g* where, as it flowed to the well more rapidly than the oil, it also flushed the oil toward the well. This resulted in a less pronounced water cone together with a much better recovery of oil from tank 2 than from tank 1. The recovery figures (Table II.) show that under the conditions in tank 1 the rate of fluid movements increased very slightly during the experiment, whereas in tank 2 the rate of flow underwent a decided increase as the oil was driven out of the relatively fine sand *d* into the overlying coarser sand *g*. This is explained by the fact that as the oil in the fine sand (tank 2) was displaced by water, the resistance to flow through the fine sand progressively decreased. Again, in the overlying coarser sand there was comparatively little resistance to the combined movement of oil and water to the well. The oil in the coarse sand in tank 2 was not only easily flushed to the well by the more rapidly flowing water, but resistance to flow through that sand also progressively decreased as the oil was expelled. The changes in the directions of flow through

tank 2, in following the paths of least resistance, are shown by the arrows on Plate III., *D* and *F*.

In tank 1, the comparatively great resistance to flow, and the barrier effects in the fine oil-saturated sand overlying the coarser sand, more especially along the contact between the two sands,

TABLE II.

VOLUMES OF OIL AND WATER RECOVERED DURING EXPERIMENT 1.

Total Time of Extraction in Minutes.	Volumes Expressed in Centimeters.					
	Tank 1.			Tank 2.		
	Oil.	Water.	Total.	Oil.	Water.	Total.
20	975	130	1,105	1,050	trace	1,050
40	1,825	450	2,275	2,493	1,520	4,013

caused the paths of flow and the resistance to fluid movements to remain more nearly constant. Comparisons of the photographs on Plate I. show the differences in the water-cone effects and the comparatively great restriction of the fluid movements in tank 1 as compared with those in tank 2. In view of the facts that have been set forth it is important that under the conditions of texture and bedding in tank 1 the rate of recovery of oil decreased as the rate of recovery of water increased, whereas under the conditions of texture and bedding in tank 2 the rate of recovery of oil increased more than 100 per cent. as the rate of recovery of water increased. Of the four liters of oil originally contained by each tank, 45.6 per cent. was recovered from tank 1 and 62.3 per cent. from tank 2.

Experiment 1 indicates that variations in the textures and bedding of pay sands cause corresponding variations in the movements of oil and water to the wells, together with variations in the effects of water upon the recovery of oil. In the absence of expanding gas, within the ranges of certain other limiting conditions, which must be given further study, a relatively fine textured sand constituting the upper part of a water-bearing or flooded "pay" is less favorable to the recovery of oil than a relatively coarse, open textured sand at the top of such a pay,

even though the finer sand may be the more porous of the two. Where the upper parts of pay sands are of relatively coarse, open texture, water occurring in the sands with light oils of low viscosity may be distinctly advantageous to recovery by facilitating the induced segregation and accumulation of the oil into the uppermost parts of the coarse open-textured sand; by maintaining the fluid levels in the sands, thus retarding the "by-passing" of gas; and by flushing the oil to the wells. Again, where the upper parts of water-bearing "pays" are of relatively coarse, uniform texture, a well or group of wells going entirely to "edge water" is a more reliable indication of the exhaustion of the recoverable oil than where the upper parts of the water-bearing pays are of relatively fine texture.

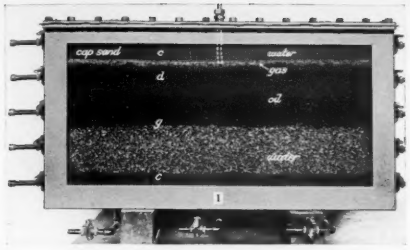
These statements must not be construed as generalizations. They apply to the recovery of *light oils of low viscosity* under field conditions that are analogous to those of the experiment, wherein the wells penetrate only the upper parts of the pays, and the propulsive force is exerted by the pressure of "edge water" advancing through beds of low dip rather than by expanding gas alone. The fact is emphasized that the relationships established through this experiment depend not only upon the textures and bedding of the sands, but also upon the *viscosities* of the oils, the proportions and pressures of compressed gases with the oils, the relative thicknesses of the various beds of sand or sandstone constituting the "pays," the initial proportions of oil and water occurring in the sands, the pressures, speed of movement, and amounts of advancing edge water, and the practice of drilling and operating the wells, more especially the depths in the pays to which the wells are drilled with respect to oil and water and the rapidity with which oil and water are then extracted. The percentage recoveries in this experiment were far in excess of what may be expected through the usual practice under ordinary field conditions.

Experiment 2 (Plate IV., *A*), illustrates further relationships between the textures and bedding of sands and the effects of water cones upon the recovery of oil. For this purpose, the pre-

ceding experiment was continued by introducing, in equal volumes through the center cocks at the ends of the respective tanks, the oil that had been recovered from each tank during Experiment 1. The fluids were then allowed to adjust themselves under hydrostatic conditions. In tank 1, the water in the relatively fine sand greatly retarded the movement of the newly introduced oil to the well, whereas in tank 2 (not shown by photograph) the oil practically filled the coarser sand around the well within one hour after it was introduced. Plate IV., *A*, shows the arrangement of the fluids in tank 1 five hours after the oil was introduced. Under hydrostatic conditions which were maintained through a period of two weeks, the further adjustments of the fluids toward the elimination of the water cone in tank 1 were extremely slow, the water in the relatively fine sand practically excluding a large part of the oil in the underlying coarser sand from migrating into the water cone area around the well.

The final phase of the experiment was an attempt to recover the oil from both tanks substantially as in Experiment 1. Under the conditions of recovery there occurred a repetition of the phenomena illustrated by Plate III. A water cone was immediately formed in tank 1 where the initial water content of the fine sand around the well caused selective permeability to water, thus facilitating the passage of water ahead of the oil. Under practically the same conditions of experimentation in both tanks a better rate of recovery of oil was obtained from tank 2 than from tank 1, but the recovery of oil from tank 1 was not so good as in Experiment 1. The rate of recovery of oil from tank 2 was practically the same as in Experiment 1, showing that under the conditions of texture and bedding in tank 2 the sands had not been injured by water coning.

Experiment 2 indicates that the effects of water cones upon the recovery of oil depend very largely upon the conditions of bedding and texture in the sands. When wells are drilled only through the upper parts of sands, and within the ranges of certain other limiting conditions, to be determined by further study, water cones are more detrimental to the recovery of oil where



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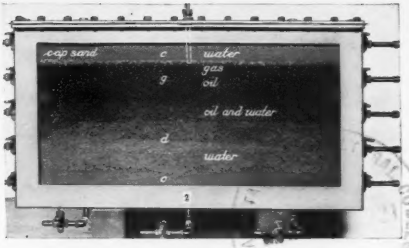

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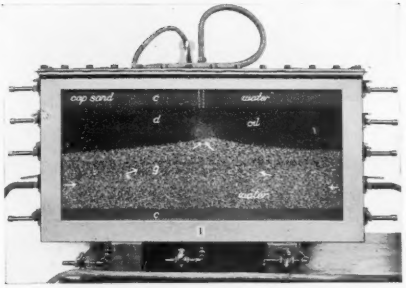

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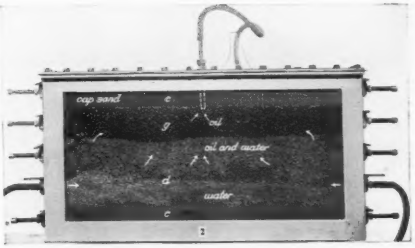

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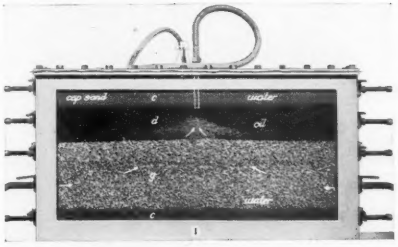

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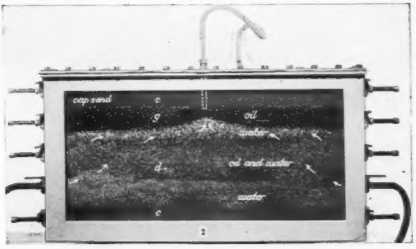


F

A. Gas, oil, and water in a pay sand, the upper part of which is of relatively fine texture.

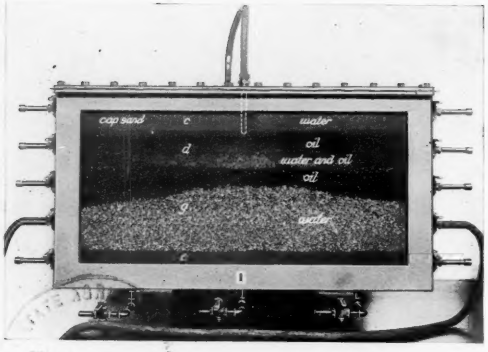
B. Gas, oil, and water in a pay sand, the upper part of which is of relatively coarse texture.

C. Water-coning effects in fine sand after extraction through the well had continued for 20 minutes.

D. Induced migration and segregation of oil from fine into coarse sand after extraction through the well had continued for 20 minutes.

E. Water-cone effects in fine sand after extraction through the well had continued for 40 minutes.

F. Water-cone effects in coarse sand after extraction through the well had continued for 40 minutes.



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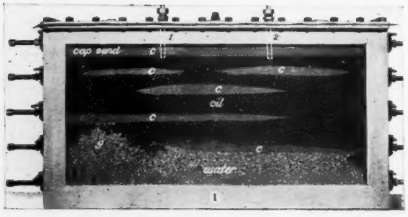

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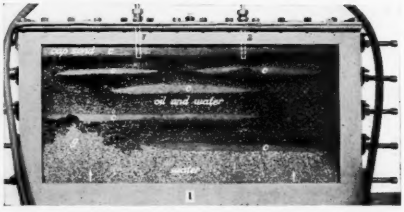


C

A. Injury to pay sand through retention of water in relatively fine sand around well.

B. Oil and water in a pay sand containing "breaks" or partings of relatively fine water-wet sand.

C. The recovery of oil and water without the formation of water cones.

the upper parts of the pay sands are of relatively fine, close texture, than where the upper parts of the pays are of relatively coarse, open texture. These relationships depend, among other things, upon the viscosities of the oils, the relative thickness of the different layers of sand constituting the "pays," the proportions and pressures of water and compressed gases associated with the oils, and the practice of drilling and operating the wells, more especially the positions and the depths to which the wells are drilled into the "pays" and the rapidity with which the fluids are extracted.

Experiment 3 illustrates further relationships that the textures and bedding in pay sands bear to the differential movements of oil and water to wells. The pay sand *g* contained thin layers or "breaks" of the relatively fine sand *c*, as shown by Plate IV., *B* and *C*. At the beginning of the experiment the sands were saturated by water (chloride brine, sp. gr. 1.100). Appalachian oil of the same quality as that used in the preceding experiments was then introduced through the openings at the ends of the apparatus. The water displaced by the oil was withdrawn through the openings at the bottom of the apparatus. Plate IV., *B*, shows the arrangement of the fluids twenty-four hours after the oil was introduced. During that time the oil in the lower left part of the tank failed to assume a flat angle of repose above the water.

Oil was then extracted through the wells under the propulsive force (3-foot head) of the water admitted at the bottom of the apparatus. Plate IV., *C*, shows the arrangement of the fluids after recovery through the wells had continued for thirty minutes. It will be observed that under the influence of differential pressures and hydraulic flow, oil penetrated the thin layers of fine water-wet sand *c*, as indicated by the dark patches in that sand. Of the 4.4 liters of oil introduced into the tank, 2.7 liters (61.4 per cent.) of the oil, together with 5.3 liters of water, had been recovered without the formation of water cones, though the production from both wells had gone almost entirely to water. The "breaks" or partings of relatively fine sand in the

"pay" caused irregular currents that evidently prevented the formation of water cones. The percentage recovery in this experiment was far in excess of what may be expected through the usual practice under ordinary field conditions.

Experiment 3 indicates that certain conditions of irregular texture and bedding in pay sands such as "breaks," or shale partings in the "pays," lying parallel with the dip may prevent the formation of water cones even though the productions of the wells tapping these sands go practically entirely to water before the recoverable oil is exhausted.

Experiment 4 (Plate V.) illustrates the effects of cross bedding in sands or inclined strata upon the induced movements of oil and water to wells. Plate V., *A,* shows the arrangement of the sands before the oil was introduced. Two of the inclined beds were moist with water as indicated on the photograph. All of the other sands were dry when put into the apparatus though water was absorbed by the dry beds along their contacts with the wet sands. The lower end of the dry bed *i* was wet by water draining downward from *b*. The wet spot appears black in the photograph. The wells consisted of ⅜ inch pipes situated one centimeter inside the plate glass fronts of the tanks and extending one centimeter below the horizontal bed of fine sand *e*. After the sands were packed into place, 13.4 liters of oil of the same quality as that used in the preceding experiments were introduced through the openings at the base of the apparatus. The air displaced during this procedure was allowed to escape through the openings in the cover plate. Plate V., *B,* shows the condition of the experiment twenty-four hours after the oil was introduced. The white patch near the base of the apparatus shows where the wet portion of the fine sand *i* was relatively impermeable to oil.

Water was then admitted through the two cocks at the lower left corner of the tank, and oil was extracted through the two wells, the propulsive force being exerted by the pressure (3 foot head) of the water. Differential movements between oil and water were at once apparent. The fluids moved parallel with the bedding rather than across the beds, but the advance of the water

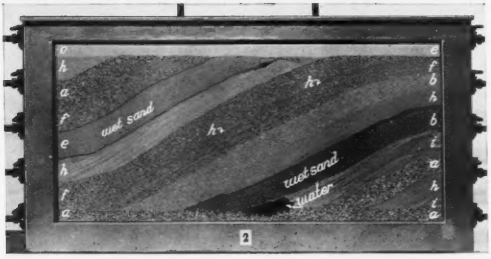
and the consequent displacement of the oil in the relatively coarse sand *f* preceded such effects in the finer sands. Oil was retained in the finer sands both above and below the more rapidly moving water. There was also a tendency for water to advance more readily into the beds that had been previously moistened by water than into the beds that were dry when the oil was introduced. Plate V., *C*, shows the arrangement of the fluids after extraction through the wells had continued for thirty minutes. Well No. 1 yielded a small amount of oil (0.5 liters) with practically no water, whereas well No. 2 yielded a relatively large amount of oil (3.5 liters) together with 2.0 liters of water. The production of well No. 2 had gone almost entirely to water when the photograph was taken. Of the oil originally contained in the sands, 27.6 per cent. had been recovered.

Extraction through the wells and also through the second opening from the top at the right end of the apparatus was continued for another thirty minutes to remove more oil. Plate V., *D*, shows the arrangement of the fluids at the end of that period. A large part of the oil had been displaced from the finer sands by water. The fluids were then allowed to adjust themselves under hydrostatic conditions for twenty-four hours. Plate V., *E*, shows the arrangement of the fluids at the end of that period. Comparison of photographs *C*, *D* and *E*, Plate V., shows that displacement and gravitational migration of the oil occurred in the finer sands under hydrostatic as well as under hydraulic conditions, though these movements and rearrangements of the oil were exceedingly slow. Oil had reaccumulated in the coarse sand *f* under well No. 2, but a large part of the oil in the apparatus was still retained as inclined bodies along the upper edges of the finer stands. It is especially interesting that oil was retained most persistently in the finest sands, and that in migrating through the finer sands and in breaking away from the fine into the coarser sands, the oil always moved to a higher position in accordance with the fundamental principles underlying the anticlinal theory rather than in accordance with capillary forces or anticlinal structures.

Experiment 4 indicates again that the induced movements of oil and water to wells are governed largely by conditions of texture and bedding in the pay sands. These relationships depend, among other things, upon the positions of the wells with respect to the bedding and textures in the pay sands. Water tends to advance and to displace oil most readily through beds of relatively coarse, open texture, whereas the oil in a flooded sand is retained most persistently in the parts of the sand that are of relatively fine texture. There is a tendency for the fluid movements to follow rather than to cross bedding planes. Cross bedding may guide the movements of oil or water toward certain wells, whereas it may retard or prevent the movements of oil or water toward other wells. Under favorable conditions, part of the oil retained in relatively fine sands may move into the coarser sands and reaccumulate in higher parts of the bed that had previously "gone to water." This reaccumulation of oil accounts, in part at least, for the successful operation of new crops of wells in certain oil fields, as in the old Pithole pool, Pennsylvania, and at Spindle Top, Texas, where the original wells "went to water" before the recoverable oil was exhausted.

Experiment 5 (Plate VI.) illustrates the retention of oil in lenses of fine sand incident to the flooding of the surrounding pay sand by water. Plate VI., *A*, shows the condition of the experiment twenty-four hours after the oil was introduced into the pay sand. Nine liters of oil and 4.5 liters of water were used in charging the apparatus, the qualities of the fluids being the same as those used in the preceding experiments. The cap sand *e* and the lower part of the coarse pay sand *a*, together with the bottom sand *e* were wet with water when they were packed into place. The upper part of the coarse pay sand *a*, together with the lenses of finer sands *h* and *j*, were dry when the oil was introduced through the openings at the ends of the apparatus.

Water was then introduced at the left, and oil and water withdrawn at the right of the apparatus, as indicated by the arrows on Plate VI., *B*. The flooding by water had progressed for one



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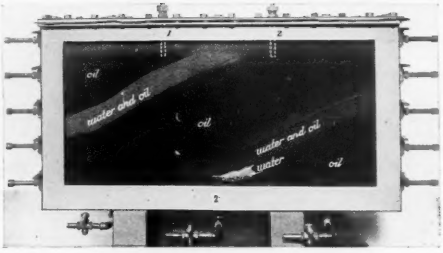

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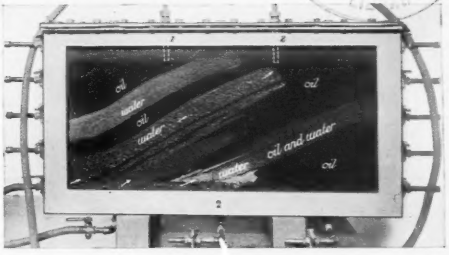

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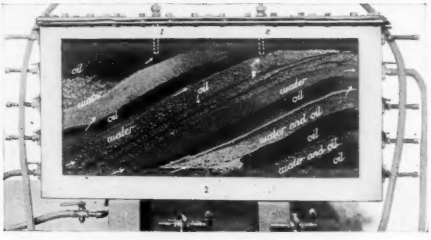

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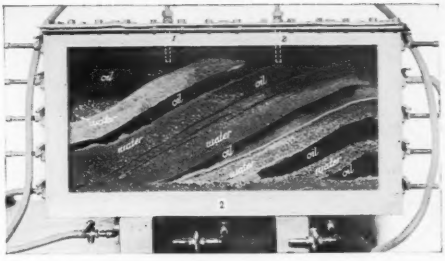

E

A. Sands arranged to simulate cross-bedding. Two of the beds were water-wet. The others were dry.

B. The same sands filled to capacity with oil.

C. The induced movements and rearrangements of oil and water after extraction through the wells had continued for 30 minutes.

D. The induced movements and rearrangements of oil and water after extraction through the wells and through the second opening from the top at the right end of the tank had continued for one hour.

E. The reaccumulation of oil around well No. 2 after the experiment had stood under hydrostatic conditions for 24 hours.

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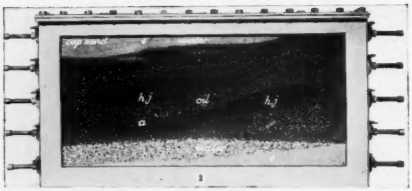

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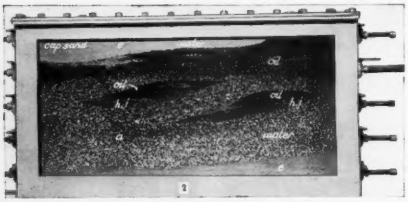

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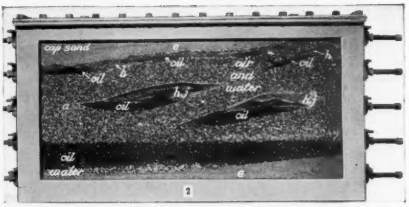

D

A. Oil and water in a pay sand containing lenses of relatively fine, close sand.

B. The retention of oil in the lenses of relatively fine, close sand, incident to the flooding of the "pay sand" by water.

C. Oil migrating upward from the lenses of fine sand and reaccumulating along the top of the coarser pay sand.

D. The retention of oil in the lenses of fine sand incident to the downward drainage of water and oil.

hour, during which 4.6 liters (51.1 per cent.) of the oil and 8.4 liters of water had been displaced from the apparatus, when the photograph was taken. Water had advanced through the relatively coarse sand *a* ahead of the oil retained in the lenses of finer sand *h* and *j*.

By discontinuing the flooding and allowing the fluids to adjust themselves under hydrostatic conditions for one week, it was found that a large proportion of the oil that had been retained in the lenses of fine sand migrated upward through the lenses into the overlying coarser sand *a*, where the oil underwent "gravitational segregation" and accumulation along the top of the coarser sand. During this migration the oil tended to accumulate in the uppermost parts of the lenses where it gradually broke away into the overlying coarser sand. Oil was retained most tenaciously in the finest parts of the lenses. This is shown by Plate VI., *C*, which was taken after the hydrostatic adjustments had continued for one week.

By draining off the water through the lower openings at the ends of the apparatus and admitting air through the openings in the cover plate, it was found that as the oil drained downward by gravity a large part of it was retained in the lenses of relatively fine sand. In the coarse sand, however, the downward migration and reaccumulation of the oil under the influence of gravity was more complete than had been the upward migration and segregation of the oil under the propulsive force of its buoyancy in water. Plate VI., *D*, shows the arrangement of the fluids forty-eight hours after the water level had been lowered by drainage. It will be observed that the fine water-saturated sand at the base of the apparatus was relatively impermeable to the oil in the overlying coarser sand.

Experiment 5 tends to substantiate the conclusion that under conditions of irregular texture much oil may be left in the relatively fine portions of sands incident to flooding by water. The experiment also indicates that under conditions of drainage by gravity, especially where water is being pumped from previously flooded sands, much oil may be left in those portions of the sands that are of relatively fine texture.

The oil that is retained in the fine parts of sands that have been saturated by flooding tends, in time, to migrate upward and to segregate and accumulate along the tops of the relatively high parts of the sands. Where the conditions are favorable, the oil tends to migrate from the relatively fine sands into overlying coarser sands, where it reaccumulates above the water.

Part of the oil retained in the relatively fine parts of sands during flooding may or may not be profitably recovered, depending upon the time required for the retained oil to migrate and reaccumulate above the water, the readiness with which the oil then moves to the wells, the amount of water to be pumped to the surface before or during the recovery of the retained oil, and the applications that are made of our knowledge of the induced movements of oil, more especially the acceleration of these movements through restoring pressures in the sands.[6] At Petroleum Center, Venango County, Pennsylvania, flooded sands are now being dewatered by improved methods of operating wells, and much of the oil that was left underground during earlier operations is being profitably recovered.

SUMMARY.

Through these experimental studies which supplement extensive field investigations, the fact is made clear that conditions of texture and bedding have an important influence upon both the natural and induced movements of oil and water through sands. Oil accumulation as well as recovery depends directly upon deep-seated movements of the fluids, and is consequently governed largely by conditions of texture and bedding. Studies of these conditions and their relations to fluid movements are of economic as well as scientific value. By demonstrating the fact that there are enormous underground losses of oil through retention in sands, and by establishing the causes for these losses, a logical step is made toward the more intelligent development and application of improved methods of recovery. With a view to contributing toward this important work, the writer outlines the

[6] See U. S. Bureau of Mines Bulletin 148.

following principles and relationships that have been indicated by the investigations herein described.

1. Variations in the textures and bedding of oil and water bearing sands cause corresponding variations in the movements of the fluids through the sands.

2. Movements of oil and water through sands tend to follow the paths of least resistance, generally through the relatively coarse, open-textured parts of the beds, the directions of movement tending to parallel rather than to cross bedding planes.

3. Frictional and capillary resistances to the movements of oil and water through saturated sands increase as the sizes of the interstices decrease. It is recognized, however, that under favorable conditions "gravitational" and hydraulic migration of oils of low viscosity occur in uncemented sands composed of grains ranging in diameter from 0.417 m.m. to less than 0.074 m.m.

4. When a water-saturated sand of irregular texture is invaded by oil, and conversely, when an oil-saturated sand of irregular texture is invaded by water, the fluid originally contained is retained most persistently in those parts of the bed that are of relatively fine, close texture.

5. A water-saturated sand of fine texture is more permeable to water than to oil, and conversely, an oil-saturated sand of fine texture is more permeable to oil than to water.

6. The selective permeability of sands with respect to oil and water is one of the factors determining the paths of least resistance to the movements of these fluids.

7. Selective permeability with respect to oil and water is most pronounced in sands of relatively fine texture.

8. As an oil-saturated sand of fine texture becomes wet or saturated with water, it becomes increasingly permeable to water and decreasingly permeable to oil. Conversely, as a water-saturated sand of fine texture becomes wet or saturated with oil, it becomes increasingly permeable to oil and decreasingly permeable to water.

9. Under conditions of rapid flow through sands of uniform texture, the differential movements of oil and water, whereby

water tends to advance ahead of oil, are more pronounced in sands of relatively fine, close texture than in those of relatively coarse, open texture. This relationship varies according to the rate of flow, and may not hold where the rate of flow is extremely slow.

10. Under conditions of rapid recovery, water cones are more readily formed, and are more detrimental to the recovery of oil, in sands of relatively fine, close texture than in sands of relatively coarse, open texture.

11. Under favorable conditions, the occurrence of bedding planes together with breaks or partings parallel to the dip of a sand may retard or prevent the formation of water cones, whereas under other conditions of bedding, especially where there is cross bedding, such irregularities of texture and bedding may facilitate the formation of water cones.

12. Part of the oil retained in sands incident to flooding by water may or may not be profitably recovered. This depends, among other things, upon the time required for the retained oil to segregate and reaccumulate above the water, the readiness with which the oil then moves to the wells, and the amount of water to be pumped to the surface prior or during the recovery of the oil. Oils of *low viscosity* can be much more readily recovered under these conditions than can oils of high viscosity. Sands of uniform texture as well as those of relatively coarse open texture are most favorable for the reaccumulation and recovery of oil subsequent to flooding.

13. In sands of uniform texture (as in the Bradford sand of northern Pennsylvania and western New York) or in sands where the upper parts of the pays are of relatively coarse, even texture (as in the Keener sand of southeastern Ohio), especially if the gas pressures have been depleted, edge water advancing under hydrostatic pressure in flat lying beds may assist in the recovery of oils of low viscosity. The water may benefit favorably situated wells (that is, wells tapping the relatively high parts of the sands or parts of the sands that are favored by conditions of texture and bedding), by facilitating induced segrega-

tion, by maintaining fluid levels in the sands, thus retarding the by-passing of gas, by exerting propulsive force, and by flushing oil toward the wells. These relationships do not hold for oils of high viscosity.

14. Where the upper parts of the pays are of relatively fine texture, especially, where the gas pressures have been depleted, edge water advancing under hydrostatic pressure may cause the loss of much oil through entrapment and retention in those parts of the sands that are of relatively fine texture. This is especially true where the oil in the fine or tight sand is left behind by water advancing more rapidly through those parts of the sands that are of relatively coarse open texture. Under such conditions, oils of high viscosity are subject to greater loss through retention than are oils of low viscosity.

U. S. BUREAU OF MINES,
WASHINGTON, D. C.

THE MAGNETITIC ORES OF NORTH CAROLINA—THEIR ORIGIN.[1]

W. S. Bayley.

INTRODUCTION.

When Mr. Keith[2] mapped the Cranberry Quadrangle in North Carolina, he had occasion to study the magnetic iron ore deposits of the Cranberry Mine. He described these deposits as occurring in a gangue of hornblende, pyroxene, and epidote, with a little feldspar and quartz and a few unimportant minerals. The ore and gangue, he states, occur as a series of great lenses lying parallel to the planes of schistosity in the gneissic granite by which they are surrounded. The ore is described as being found in the gangue in the shape of smaller lenses varying from a few inches to 50 feet in thickness, and from 2 to 5 times as long. The ore lenses are said to have sharp limits in some cases but usually to grade into the gangue. Moreover, ore is sprinkled through the gangue, and more or less gangue is scattered through the ore.

The minerals composing the ore and gangue were thought to have been deposited long after the enclosing granite and after the deformation that produced its schistosity, since they "are only slightly crushed or rearranged, although they are the same varieties which in adjacent formations show the greatest metamorphism." The ore may "have replaced a pre-existing mass of rock by solution and substitution of new minerals, or it may have been deposited from solution in open spaces in the enclosing formation."[3] It appears to Keith more probable that the ore

[1] Published with the permission of the Director of the United States Geological Survey and of the State Geologist of North Carolina.

[2] Arthur Keith, Cranberry Folio (No. 90), Geol. Atlas U. S., U. S. Geol. Survey, 1903, p. 8.

[3] *Idem*, p. 8.

replaced an igneous, diabase-like mass that intruded granite, although he does not presume to say why other diabase-like masses in the granite were not similarly replaced. He concludes that since the magnetite deposits are later than the folding movements in the district, and since an adjacent gabbro, "the Bakersville gabbro," is also later than these movements and the magnetite bodies swing around the circumference of an area of the gabbro, "the magnetites are due to alterations begun by the gabbro intrusions." However, since there are no "later intrusions" of gabbro or diabase in Ashe County where magnetites similar to the Cranberry magnetites occur, the ore in this region cannot have been produced by the process outlined. Mr. Keith thought that the iron in Ashe County may have been dissolved from the Roan gneiss[4] through which the mineralizing solutions must have passed in more than one epoch.

With reference to the titaniferous magnetites which are abundant in the same general areas as non-titaniferous varieties, he states that the depositing solutions in the two cases were probably active at different times.

TITANIFEROUS AND NON-TITANIFEROUS MAGNETITES.

In the summer of 1919 an examination was made of the magnetites of western North Carolina at the instance of the North Carolina Geologic and Economic Survey, and some facts were observed that seemed to throw doubt upon Mr. Keith's theory as to the origin of the Cranberry ore, and to throw some light on the cause of the difference in the titaniferous and non-titaniferous magnetites.

That the two classes of magnetite are essentially different is indicated clearly by their analyses. The non-titaniferous varieties contain not more than .25 per cent. of TiO_2. They usually, however, contain also manganese. The titaniferous varieties that have been analyzed contain from about 4.5 per cent. to about

[4] The Roan gneiss is a pre-Cambrian series, made up mainly of basic tuffs and sills or flows of diabases, gabbros and diorites, that have been largely changed to schists and gneisses.

41 per cent. of TiO_2. They contain almost no manganese, but always a small quantity of Cr_2O_3.

ORIGIN OF THE TITANIFEROUS ORES.

The gangue of the non-titaniferous magnetite is nearly always characterized by an abundance of epidote. There are also associated with it nearly always large quantities of hornblende and quartz. Moreover, pegmatites cut through the ore and gangue in an intricate manner, and much of this pegmatite contains as one of its components, lenses and irregular masses of magnetite. The titaniferous ores are characterized by none of these features. They are usually distinct veins of magnetite that cut through hornblendic rocks that frequently contain fibrous minerals. In one case a titaniferous ore is closely associated with a fresh peridotite. It is unnecessary to go into further detail with reference to the associates of these ores. It is sufficient to state here that in every case the microscope shows the titaniferous ores to be associated with decomposition products that were probably derived from peridotites. The peridotites are schistose, the magnetite is in many cases broken, and the magnetite grains are often partially changed to rutile. It is thought that in these cases the magnetite was associated in origin with the peridotite, and the presence of chromium in them seems to substantiate this inference.

CHARACTER AND AGE OF THE CRANBERRY NON-TITANIFEROUS MAGNETITE ORE.

The study of the Cranberry ore shows an entirely different paragenesis. Epidote, hornblende, quartz, and magnetite are the predominant components. The epidote is unquestionably derived from the plagioclase of pegmatites. The hornblende is probably derived from pyroxene, as pyroxene centers are discoverable in many of the larger grains. In addition, there is also often much quartz present. The most striking feature of thin sections made from ore and gangue is the granulation of the quartz and

the feldspar. In many cases, too, the magnetite grains are broken and their parts separated. The amount of crushing suffered by the constituents of the vein is even greater than that suffered by the surrounding granite, if one may judge from the appearance of the thin sections. This is directly in opposition to Keith's view that the deposit was made after the deformation of the region. There seems to be no question but that the ore of the Cranberry deposit was made before the date (Juratrias) assigned to the intrusion of the Bakersville gabbro. If this is true, the origin of the magnetite cannot be correlated wth the intrusion of this gabbro,[5] if its age is post-Paleozoic.

The Ore Vein at the Cranberry Mine.—Naturally the best exposures of the ore-deposit are in the large open cut at the Cranberry Mine. On its walls are excellent illustrations of the relations of the various phases of the vein-filling to one another. The vein here is about 80 feet wide. It comprises a plexus of rocks in the midst of which occurs the commercial ore as a series of lenses, which so far as development has gone, appear to have no pitch. The plexus is cut by pegmatite and by veins of almost pure magnetite. The pegmatite cuts irregularly through the vein plexus twisting and turning in a complicated way and gradually fingering out. In some places it encloses lenses of ore and in others lenses of coarse, green hornblende. In places it cuts comparatively cleanly through the other rocks, often with only one sharp wall, rarely with both walls sharp. Usually the walls are indefinite—the pegmatitic material grading into gneiss, so that frequently there is a little seam of gneiss between the pegmatite and the vein matter.

The main portion of the vein, aside from the horses that occur in it and the veins of pegmatite and magnetite, consists of masses of hornblende, or of hornblende and magnetite, of hornblende and epidote, of epidote and magnetite, or of epidote and quartz.

[5] Numerous sections made from specimens collected in the area indicated by Keith, on the Cranberry Folio, as being underlain by the Bakersville gabbro, reveal a metamorphosed basic rock in which there has been a great deal of crushing. The sections are similar in their features to those made from specimens taken from the more massive layers of the Roan gneiss.

All are slightly schistose parallel to the strike of the vein, and some of them are well-defined gneisses. Especially is this true of the aggregates containing epidote.

The epidote which is so abundant everywhere is apparently an alteration of feldspar. Some specimens show a continuous gradation from one mineral to the other. Others show a graphic arrangement of quartz and epidote identical with that exhibited by quartz and feldspar in graphic-granite. Others show veinlets of epidote extending from large masses of pegmatite into adjacent rocks like the ordinary veins of feldspar so frequently found radiating from pegmatite masses. In rare cases veins of epidote and quartz pass into veins of magnetite along their strikes, apparently indicating that the two were introduced at the same time. That they were once part of the same intrusion is indicated also by the fact that epidote and magnetite are everywhere closely associated.

The magnetite is closely associated with the pegmatite. The miners declare that the richest ore is always near pegmatite. The pegmatite and magnetite veins both cut the lean ore, which is the mixture of hornblende and magnetite referred to above, in the same way, and magnetite impregnations extend from the walls of the magnetite veins into the bordering rocks, causing an enrichment of these, and giving rise to magnetite gneisses. Moreover in many instances magnetite forms a constituent of coarse pegmatite, exactly as does feldspar, quartz and hornblende. It has the same shapes as the other components and the individual grains, when not aggregated, are of the same sizes as the grains of quartz, hornblende and feldspar. More frequently, however, the magnetite forms groups, either alone or with hornblende, and these constitute lenses in the pegmatite. There is a strong tendency for the hornblende and magnetite to occur together. They appear to be among the last components to separate, and often they occur in great masses forming lean ore deposits. Of the two, perhaps magnetite is the later since veins of this mineral penetrate the lean ore. It is probable, however, that the magnetite separated in two stages, of which one

was contemporaneous, or nearly so, with the great mass of the hornblende, and the other was distinctly later. Where the two minerals occur together in the lenses the hornblende is apt to occur on their borders with the magnetite in their centers, and where arms extend into the surrounding quartz-feldspar mass the main portions of the lenses may be composed of magnetite or a mixture of magnetite and hornblende, while the extensions consist entirely of hornblende.

The Pegmatites.—In thin section under the microscope all of the pegmatites, which were originally augite-syenite pegmatites, show that they have been subjected to deformation processes. Their plagioclase, which is mainly andesine, is shattered and cracked. Their twinning lamellæ are gently curved or are bent at sharp angles at cracks which cross them. These cracks may be healed with quartz or they may be filled with epidote. Throughout the feldspar epidote particles are common. They appear in individual crystals or as groups of grains, but the mineral is most abundant near contacts of the feldspar with hornblende. At such contacts the feldspar is entirely replaced by epidote, and this is also the case where the feldspar has been broken into small fragments. Between the feldspar grains is a mosaic of quartz and fresh, untwinned feldspar, with an occasional grain of microcline and often grains of epidote. The constituents of the mosaic frequently possess a parallel elongation. Here and there are areas in which a few large quartz grains are observable. These perhaps are the remnants of original quartz components of the pegmatite, since they are always divided into differently oriented sectors all of which show wavy extinctions, while the smaller components of the mosaic are homogeneous throughout and extinguish sharply. In some instances, more particularly in the triangular patches of mosaic between several neighboring feldspars, are small masses of calcite. Since these show comparatively few twinning bars they are inferred to be secondary.

The hornblende, which is present in nearly all specimens of the pegmatite that have been seen, is apparently all secondary.

It occurs in large compact masses that are partial pseudomorphs of pyroxene and in plates, fibres and acicular crystals, either forming groups or occurring as individuals scattered through portions of the quartz-mosaic. Within the large compact masses there are often remnants of a partially uralitized pyroxene which is slightly pleochroic in yellowish green tints. This is surrounded by a zone of compact strongly pleochroic uralite, and around this is a border of spicules of the same uralite. Some of these extend across little veins of quartz mosaic and join neighboring compact uralite masses. Many of the pyroxene remnants, like the feldspars, are fractured, and into the fracture cracks quartz or quartz and epidote have been forced. The compact hornblende which is not demonstrably derived from pyroxene is in large crystals that have the sieve structure characteristic of minerals of metamorphic origin. In them are numerous quartz and epidote grains and occasionally little nests of calcite. In several instances scattered through the hornblende are the little regularly arranged platy inclusions characteristic of diallage in gabbros. The greater part of the hornblende, however, is a mass of small crystals and fibres intermingled with small quartz grains, a few tiny grains of epidote, and little nests of calcite.

The Gneisses.—The gneisses that constitute such a large proportion of the vein matter are medium-grained schistose aggregates of epidotized feldspar, hornblende, magnetite and a little quartz in which the pencil structure is prominent, or of fresh feldspar, quartz and magnetite. There is no reason to suppose that the magnetite does not bear the same relation to the other components as does the hornblende, or as does any femic mineral in any gneiss with a structure that is original. The gneiss in the vein-mass (exclusive of that forming "horses") of the Cranberry vein is believed to be an igneous rock closely related to the pegmatite, and its structure is thought to be the result of crushing and recrystallization under movement in the plane of the vein.

Relations of the Rocks in the Vein-Mass.—The relation of the pegmatite to the coarse hornblende masses is difficult to de-

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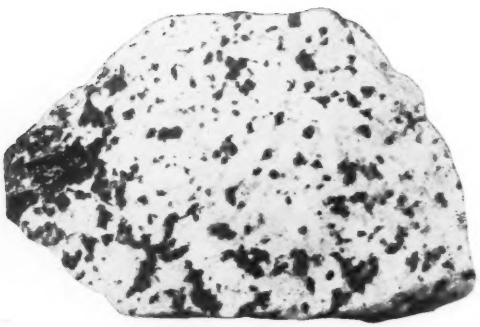

B.

FIG. *A*. Magnetite ore from Cranberry Mine, showing mixture of hornblende and magnetite (right) associated with epidotized pegmatite (left). The small gray grains and layers of grains are magnetite. x ½

FIG. *B*. Marble-magnetite ore from Lansing, Ashe County. x ⅘.

termine. In some specimens the pegmatite appears to be older than the hornblende, but in most cases it is later. It intrudes the hornblendite in distinct dikes and little stringers all running in the same direction forming a gneiss, and it also crosses little streaks of the hornblende and surrounds little islands of this rock. The gross aspect of specimens showing these relations is that of an injection gneiss.

In the case of the epidote-hornblende-magnetite gneisses the hornblende and magnetite appear to be contemporaneous, but distinct and definite layers of magnetite and hornblende cut across the schistosity of the gneiss in such a way as to leave no doubt that the material of the gneiss is the older. Moreover veinlets of magnetite cut the gneiss as do also little veins of quartz. In other cases almost pure magnetite sends tongues into epidotized pegmatite. In most cases there is a little layer of hornblende between the epidote and the magnetite in the tongues and not infrequently the magnetite plays out and is replaced by hornblende.

The Ore.—The lean ore has been described as a mixture of hornblende and magnetite. (See Plate VII, *A*, right side.) Usually the two are uniformly intermixed, but in some cases the magnetite is scattered as tiny grains through the hornblende and again it occurs as little streaks and lenses in the midst of a granular hornblende aggregate. As the ore becomes richer in grade the magnetite is seen to become more and more abundant and the hornblende naturally less abundant until in the richest ore of this type the mass is a fine-grained aggregate of magnetite grains 1 mm. and less in diameter, with here and there a grain of hornblende, a rare grain of epidote, an occasional grain of quartz and little nests of calcite. A few white sugary quartz veins run through the mass and there is in it a very obscure schistosity. In many cases where the schistosity is a little more marked than elsewhere the more highly emphasized structure appears to be due to magnetite which is much more abundant in certain layers than others—either as many little lenses embedded in sparse hornblende or as numerous grains that are scattered through the hornblende in some layers, while entirely absent from other layers.

In either case the magnetite is not sharply separated from the surrounding hornblende nor are the layers rich in magnetite sharply separated from those composed exclusively of hornblende. The portions rich in magnetite grade into those containing little of this mineral, and in many cases it is impossible to designate on hand specimens any definite lines between them. The relations of the magnetite to the hornblende suggest strongly that a schistose hornblende rock has been impregnated by magnetite and that the result is a magnetite-hornblende gneiss analogous to the impregnation gneisses so common in areas of old rocks.

In a second type of ore an enrichment in iron has been brought about by a later contribution of magnetite in the form of veins that cut the lean ore. These veins vary in width from a small fraction of an inch to several feet. With increase in their number and thickness the lean ore rapidly changes to a high grade ore, the highest grade being that of the thicker veins. In some cases these are wide enough to furnish fragments that can easily be separated by hand from the run of the mine and saved for a special grade of the highest quality ore. The material of these veins is usually a mediumly coarse-grained aggregate, composed entirely of magnetite. The grains have average diameters of about ¼ inch though many of them are much larger than this. They are black and have a brilliant luster, in which respect they are distinctly different from the titaniferous magnetites, which have the color and luster of steel.

ORIGIN OF THE CRANBERRY ORE.

These relations of pegmatite, gneiss, hornblendites and magnetite suggest that they are all parts of a contemporaneous intrusion that took place before the general deformation of the mountain region was concluded. The intrusion was apparently a magnetitic pyroxene-pegmatite, followed later by an intrusion of pyroxene-magnetite and finally by one of magnetite. According to this view the magnetites of North Carolina originated in pretty much the same way as those of New Jersey. In the northern

State the iron ore was brought up by pegmatites that were differentiates of some igneous mass beneath. In North Carolina a similar origin is postulated. In both States intrusons of less silicious ferriferous liquids followed the more silicious magmas. In New Jersey the intrusions are thought to have taken place in pre-Cambrian time, because no pegmatites are known there that are of later age. In North Carolina the severe deformation of the material of the deposits indicates that they were formed earlier than the end of Paleozoic time, and since no pegmatites are known to exist in the Paleozoic rocks, it is probable that they were formed in pre-Cambrian time. The source of the liquids is not known, but they might well have come from the magmas that furnished the gabbros, diorites and other basic sills, etc., in the Roan gneiss series.

ANALYSES OF MAGNETITE ORES FROM NEW JERSEY AND NORTH CAROLINA.

	A.	*B.*
Silica, SiO	14.28	8.48
Alumina, Al_2O_3	1.08	.86
Ferric oxide, Fe_2O_3	50.35	55.99
Ferrous oxide, FeO	28.30	26.98
Magnesium oxide, MgO	0.62	1.89
Calcium oxide, CaO	5.18	2.42
Soda, Na_2O	0.37	0.33
Potash, K_2O	Trace	0.19
Water, minus, H_2O	0.04	0.15
Water, plus, H_2O	0.17	
Titanium oxide, TiO_2	.12	1.01
Carbon dioxide, CO_2	None	
Phosphoric acid, P_2O_5	None	1.54
Sulphide, S	None	0.008
Sulphate, SO_3	Trace	
Vanadium oxide, V_2O_3	None	0.08
Manganese oxide, MnO	0.18	0.02
Chromium oxide, Cr_2O_3	None	None
Barium oxide, BaO	None	None
Strontium oxide, SrO	None	None
Fluorine, F	None	0.08
Total	100.69	99.948

A. Selected sample of ore from Cranberry Mine, N. C.

B. Sample of shipping ore from South vein of Richard mine, Morris Co., N. J. ("Iron Mines and Mining in New Jersey," Vol. VII. of Final Report, Geol. Survey of N. J., 1910, p. 113.)

A comparison of the analyses of the New Jersey and North Carolina magnetites reveals their similarity in character, and might well suggest for them a similarity in origin.

It has been suggested by some geologists who have seen the Cranberry deposits that they may represent a replacement of limestone. There is calcite in some of the sections made from the Cranberry rocks, but it all appears to be secondary, like that in the granites of the district, though there are places in the mine where there is much garnet which might well represent remnants of a metamorphosed limestone. However, if the vein represents an old limestone mass, it was in the form of a sliver only 80 ft. wide and 22 or more miles long—which is improbable, or of a series of lenses limited to a zone with the dimensions given, which seems equally improbable, in view of the fact that nowhere else in the region are there any evidences of the presence of limestone lenses in the crystalline rocks, except at two points where the limestone is distinctly recognizable as such.

There are known to be magnetites in Ashe County which are partially replaced limestones, but they are very different from the Cranberry ore. At Lansing a partially replaced limestone is mined. The ore is a mixture of calcite, dolomite, magnetite and various amphiboles, and in places it contains red garnet (Plate VII, *B*.) Epidote, which is so common in the Cranberry deposits, is absent from that at Lansing and the whole aspect of the two ores is different. (Compare Plate VII, *A*).

University of Illinois,
Urbana, Ill.

DISCUSSION

This department has been established by the editors in order to afford to those interested in questions relating to economic geology an opportunity for informal discussion. Contributions are cordially invited either in the form of discussion of more formal papers appearing in earlier numbers or bearing upon matters not previously treated. Letters should be directed to the Editor, Sheffield Scientific School of Yale University, New Haven, Conn. The full name of the author should be attached to all communications.

VEIN FILLING AT BENDIGO, VICTORIA.

Sir: In ECONOMIC GEOLOGY, June, 1920, Mr. Waldemar Lindgren expresses doubt relative to the importance of replacement at Bendigo and to the theory of the formation of the gold bearing quartz veins that has been advanced in my publications. Mr. Lindgren bases his doubt on a specimen of quartz showing a crustification of ankerite, but he does not bring forward anything to cause me to reconsider my conclusions. It seems to me that there are aspects in the work of Prof. S. Taber, as well as in my own, that have not yet been considered by him.

Mr. Lindgren's Description of Quartz Specimen.—Mr. Lindgren states that "on the whole the metasomatic action of the vein-forming solutions on the black slate is very slight, often entirely imperceptible. In places a little pyrite has developed in the country rock and some sections show a little carbonization of the slate." Pyrite, arsenopyrite and ankerite are widely, and in places thickly, disseminated through the slates and sandstones of Bendigo. Their presence indicates a slight replacement of the country rock, but the extent of replacement in the reefs is indicated by the lines of carbonaceous matter which, I consider represents the residues from replaced country rock. The evidence for this view is set forth in detail in my publications in Australia,[1]

[1] "Factors Influencing the Gold Deposition in the Bendigo Goldfield." Bulls. Nos. 4 (1917) 8 (1918), 16 (1919). Commonwealth Advisory Council of Science and Industry.

summarized in my paper in ECONOMIC GEOLOGY, March, 1918, and amplified in my letter to ECONOMIC GEOLOGY in August, 1919. A form of occurrence of these carbonaceous residues is illustrated in the accompanying photograph (Fig. 17) of a spur in slate simulating the arched form of a saddle reef at the 568 ft. level in the Great Northern Mine. The laminæ in this spur are

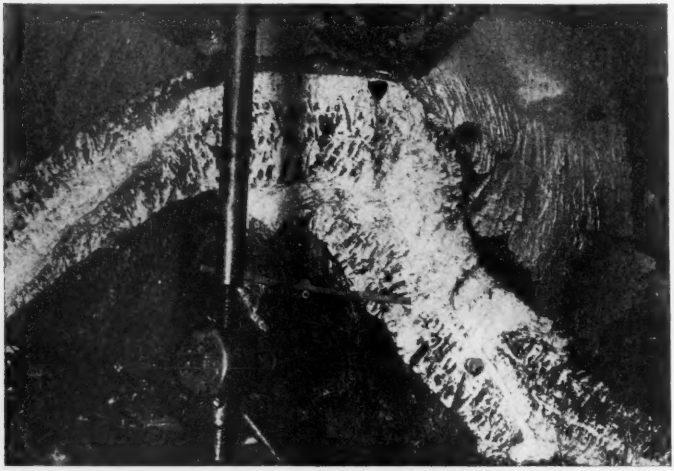

FIG. 17. Spur in slate 568-foot level Great Northern Mine, simulating saddle reef but crossing bedding planes shown in upper left corner. The spur shows areas of dark mottled quartz, some of which in section at right angles to photo are similar to quartz with "preserved brecciation"; others are groups of fine carbonaceous laminæ.

similar to those in the specimen of "preserved brecciation" illustrated in plate V. in ECONOMIC GEOLOGY, March, 1918. This spur has been mined during the past eight months and has produced 419 oz. 17 dwts. of gold from 2,065 tons, exclusive of the gold from the copper plates and pyrites. Replacement is considered to be important at Bendigo because the laminæ are abundant in the reefs, because a large proportion of the free gold in the reefs is concentrated along the track of one or more of

these laminæ, and partly because it is an essential feature in the explanation of the sporadic occurrences of the gold, chlorite and aggregates of scaly white mica, of the passage of white mica into chlorite, and of the similarity of the white mica in the reefs to the white mica in the slates.

There can be little doubt that the quartz specimen collected by Mr. Lindgren from a dump heap at Bendigo is a fragment of a quartz spur. He states that "the specimen shows an irregular opening in the slate filled by ankerite and quartz. The large opening is simply an enlargement of the bulging slate lamellæ." In my opinion his specimen shows, not an opening, but a vein of quartz in slate.

The quartz in his specimen contains slate inclusions which are stated to be "not unsupported but connected with the main mass of slate on the reverse side of the specimen." This may be correct in a specific case but it cannot discountenance the fact that mining operations at Bendigo will prove over and over again to any continuous observer that the Bendigo reefs contain many inclusions of country rock both small and large, which are not in any way supported by the walls of a reef.

Mr. Lindgren states that "the main mass of the quartz filling consists of large individuals showing crystal outlines and being absolutely free from optical disturbances." I have also observed quartz crystals from the Bendigo quartz reefs free from undulose extinction between crossed nicols, but in a collection of 112 rock sections that I have at hand, made from specimens of all types of quartz reefs from all parts of the Bendigo field, there is not one section in which the quartz does not show the optical strain phenomena. In some cases it is as strongly marked as in a metamorphic gneiss or schist. In some cases it is undoubtedly more prominent in the quartz of the quartz reefs than in the detrital quartz of the adjoining sandstones.

Occurrence of Ankerite.—Mr. Lindgren's specimen does not furnish a complete account of the occurrence of ankerite in the Bendigo reefs and his "open space" theory neglects a number of related facts. His specimen comes from a spur but the features

are not characteristic of all spurs. The crustification is absent from many spurs and, if present, may be confined to one part of the spur. In some cases it is found on one wall only and even then it may be discontinuous and irregular, while the spur itself maintains a uniform width. If present on both walls of a spur its distribution is often quite unsymmetrical. It is sometimes more noticeable in the small branching ramifications of a large spur and curiously the width of the layer of ankerite is approximately uniform, no matter what the width of the spur may be. If ankerite is present in the body of the spur it may surround angular inclusions or it may occur as seams attached to thin carbonaceous laminæ, of the same width as the layers on the walls. These included seams may only be an inch or so in length and similar seams form the characteristic occurrences of ankerite in the laminated or bedded reefs. Rarely does the ankerite line the walls of a laminated reef. Occasionally crystals of ankerite or calcite occur mingled with the main body of the quartz reefs or in vugs.

When a gold-bearing spur shows the ankerite crustification the gold occurs chiefly along the junction of ankerite and quartz, either along the walls or included seams. When the spurs cross alternating beds of slate and sandstone, much of the ankerite as well as the gold is frequently confined to the portion of the spur bounded by slate. If ankerite is present in the payable laminated reefs as in the illustration the gold is mostly between the quartz and the ankerite. Sometimes it is embedded in the ankerite.

Mr. Lindgren's Explanation.—Mr. Lindgren pictures a cavity which remained open until a coating of ankerite was deposited, the character of the solutions changed and the quartz deposited. Consistent with this view and the above facts of occurrence, it must be urged in respect to the gold-bearing spurs that, after the deposition of the ankerite on the walls of the cavity, the solutions changed and gold was deposited, and then the solutions changed again and quartz was deposited. Such a simple explanation fails completely when applied to saddle reefs and no one familiar with the eccentric and sporadic nature of the Bendigo gold shoots has

been able to explain their localization by simple variations of the composition of the primary solutions. The enrichments are not secondary, are related to faults and vary in a remarkable manner within short distances in a reef that is otherwise uniform and regular, and a satisfactory explanation must take cognisance of these facts.

Replacement of Ankerite.—Mr. Lindgren concludes that in his specimen the quartz partially replaces the ankerite because (1) the ankerite is corroded by the quartz, and (2) the presence of intersecting veinlets of quartz in the ankerite. I do not attach much weight to the first reason because in the same way quartz crystals can be observed corroding other quartz crystals. If the argument is followed to its logical conclusion one must consider that the other minerals in these reefs, gold, galena, blende, pyrite and arsenopyrite are all replacing one another in turn and the argument follows a circle. I do not regard the second reason as satisfactory evidence of replacement as there is an alternative explanation. It indicates that the intersecting veinlets of quartz are later than the ankerite but, if the deposition of ankerite and quartz is a continuous process, it is conceivable with the aid of the theory of growth, that in the last stages of vein deposition small veins of quartz can form in the ankerite in the same way that the larger veins of quartz and ankerite have developed in the country rock, *i.e.*, by gradual growth and the pushing apart of the vein walls. The small veins do not as a rule intersect the larger quartz crystals because so long as a supply of saturated solution is available the large crystals continue to grow in preference to the creation of new centers of crystallization. The supply of saturated solution can find access to the growing crystals either through the pores of the bounding rocks or along the course of the vein. I fail to see why the large size of the quartz individuals indicates high temperature conditions as Mr. Lindgren suggests.

Force of Crystallizaton.—Mr. Lindgren is not prepared to admit that the force of crystallization is able to force apart the walls of a vein and maintains that the crustification of ankerite

indicates the existence of a cavity. He allows that the force of crystallization may exert some minor action, but a cavity is necessary. Mr. Lindgren's present view is therefore in accord with E. J. Dunn's view of the Bendigo quartz reefs.[2] In opposing view are the researches of Prof. Taber,[3] who has demonstrated experimentally that veins can be formed in this manner by the force of crystallization without any preëxisting cavity and that, at the same time, by slightly changing the composition of the vein-forming material a crustification can be produced along the walls of the vein.

The force of crystallization necessary for the development of veins within the walls of a porous pot under laboratory conditions is more easily understood than that necessary for the development of veins buried hundreds of feet below the surface of the earth. Still the end products under the artificial and natural conditions are so similar that the argument by analogy is overwhelming and in this respect it is to be regretted that the results of Taber's experiments are not recorded by photographs. The conception is not so difficult when it is recollected that Becker and Day[4] attempted to measure this force but could only conclude that the force of crystallization was of the order of magnitude of the crushing strength of the rock. My own researches have shown that once the growth-theory is clearly pictured a considerable advance is made in the understanding of the detailed structure and characters of the Bendigo quartz veins. The theory of open cavities hundreds of feet below the surface, advocated by Lindgren, neglects the experimental evidence, involves a conception that is, in my opinion, more difficult and further produces confusion in the mind of the observer who seeks to picture the development of all the peculiarities and variations in these veins.

[2] "Report on the Bendigo Goldfield," E. J. Dunn, Spec. Rpts. Dept. Mines, Victoria, 1896, p. 22.

[3] "Growth of Crystals under External Pressure," S. Taber, *Amer. Journ. Sci.*, 4th ser., vol. XLI., 1916, p. 546.

"Mechanics of Vein Formation," S. Taber, *Trans. Amer. I. M. E.*, Sept., 1918, p. 1191.

[4] "Linear Force of Growing Crystals," *Proc. Wash. Acad. Sci.*, vol. VII., 1905.

Force of Crystallization Combined with Replacement.—The formation of a vein by replacement is a process that must necessarily be considered in conjunction with a theory of growth from fractures. Irving pointed out[5] that a newly-formed replacement ore body is sufficiently porous to allow the passage through it of further supplies of mineral solutions. If, then, crystals of quartz or any other mineral are first formed by replacement and the supply of saturated solution continues, these crystals of quartz can continue to grow and make room for themselves by the force of crystallization. The width of a reef may thus be much greater than the width of a replaced bed. This theory is helpful in picturing the development of the gold shoots in Bendigo's quartz reefs, but it is incompatible with Mr. Lindgren's view of the nature of replacement.[6] Mr. Lindgren considers that the volume of a replacing mineral equals the volume of the mineral replaced in rigid rocks. He has, however, stated that the force of crystallization and replacement probably coöperate in soft clays, while denying it in the case of rigid rocks. Once it is admitted that the force of crystallization can push aside the walls of a vein Mr. Lindgren's case for his "law" of equal volume is weakened.

If the processes of replacement and growth are combined and simultaneous it becomes a matter of speculation as to how much of a particular reef is due to replacement and how much is due to growth. It seems probable from the distribution of unreplaced resides that in the larger reefs of Bendigo more quartz is due to growth than to replacement, and that in the small laminated saddle reefs and leg reefs the replacement process is relatively more important, but even in these cases as much or more quartz may be due to growth as to replacement.

F. L. STILLWELL.

BENDIGO, AUSTRALIA.

[5] "Replacement of Ore Bodies," J. D. Irving, ECON. GEOL., VI., 1911, p. 527.

[6] "Nature of Replacement," W. Lindgren, ECON. GEOL., VII., 1912, p. 533.

REVIEWS.

Mineralogy. An Introduction to the Study of Minerals and Crystals. By E. H. KRAUS and W. F. HUNT. 561 pp., 696 figs. in the text. McGraw-Hill Book Co., 1920. Price $4.50.

So many books on elementary mineralogy have been published during the last decade that one is inclined to examine a new one rather critically to discern the justification for its addition to the list. It would seem, however, that in the present instance the authors have been able to produce a book in a number of ways different and better than its predecessors.

It should, perhaps, not be called strictly an addition to the list of mineralogies, because, although it is apparently mostly newly written, other books by the same authors covering largely the same field have been in print for a number of years.

This book covers the following fields: crystallography, physical properties of minerals, chemical properties and qualitative blowpipe methods of determination, formation and occurrence, descriptive mineralogy, gems and precious stones, lists of minerals according to elements, determinative tables based upon physical tests. The chapter on crystallography is well written and illustrated. The chapter describing the optical properties of minerals is too brief to be satisfactory. It is a question if the attempt should be made to cover this difficult and intricate subject in an elementary book. Ordinarily, the student concerned with the optics of crystallized bodies is an advanced student and needs a complete and detailed exposition.

In the chapter on descriptive mineralogy some one hundred and fifty species are described. This chapter is fully illustrated with crystal figures and reproductions of photographs of mineral specimens. To one who appreciates the difficulty of adequately representing minerals through photographic reproduction there is a surprising number of these illustrations that are eminently successful. Yet it must be confessed that there remains a considerable number, which, if deprived of their explanatory titles, would puzzle even an expert. The determinative tables are based upon the unsatisfactory method of using physical characters. The minerals are first subdivided according to metallic and nonmetallic luster, which terms are given an unusually broad meaning.

The subdivisions are based upon color. This property is so variable that its use necessitates a frequent repetition of the same mineral in different sections of the tables. A case chosen at random will illustrate this point. The mineral siderite is described under the following headings: (1) Minerals with metallic luster, dark gray, or black in color, having a white, gray, green, red, brown, or yellow streak; (2) minerals with metallic luster, red, brown, or blue in color, having a white, gray, green, red, brown, or yellow streak; (3) minerals with non-metallic luster, dark gray or black in color, having a green, red, brown, yellow, or black streak; (4) minerals with non-metallic luster, yellow, or brown in color, having a red, brown, or yellow streak; (5) minerals with non-metallic luster, yellow, or brown in color, having an uncolored, white, or light gray streak. Because of such repetition it takes more than 160 pages to classify 150 species.

The book is well printed and on the whole successfully illustrated, and includes a great amount of information clearly and concisely given.

W. E. FORD.

The Cost of Mining. By JAMES R. FINLAY. Cloth, 6½ by 9¼, pp. 532: third edition; charts and tables. McGraw Hill Book Co., Inc., New York. Price, $6.00.

During the eleven years that intervened between the first edition of this well-known work and the present one, many changes have taken place in the mining industry. The development of new fields and new processes of ore treatment have radically changed the cost of mining in some districts. Also, the war demand for metals, fuel, and labor brought on the pyramiding of prices, costs and profits, for everyone in the mining business, labor included. It required true courage for anyone to predict the future financial conditions of any mining enterprise. How well Mr. Finlay has done this, only time can decide. He has in general given us a thoughtful and conservative discussion of what the future will be and his expectations are already, with our present industrial slump, well on their way to fulfillment.

The first thing that strikes the reader is, that it is a much more readable and complete volume than the previous editions. The typography is much clearer and the narrower margins make the net gain in reading matter much greater even than the hundred-odd added pages would indicate. The new material comprises new chapters on coal, the iron industry, the copper deposits of the southwest, and on gold and the relation of its production to prices, war, and international relations.

These new chapters and added matter in others give concise accounts of the geology of many mining districts together usually, with a pen

picture of the living conditions and other factors which help to explain the cost variation between districts. None of this added material is prosy, indeed, there is even included that 'rara avis' in a technical book, a poetic description of a Flat River, Mo., landscape. The similarity in the data furnished on the various metals, adds to the value of the book and to the coherence between sections. Another valuable addition is that of production figures up to 1918, and generally these cover the world, instead of the United States only. Throughout the book where costs are not brought up to date there is usually an added paragraph giving the more modern conditions. The chapters on costs of gold and silver mining are but slightly altered from those of the first edition and the author states that there has been "little vital change" in these industries.

The reviewer regrets that no mention was made of our recent silver boom and also that few costs were furnished on electrolytic zinc production and on leaching processes in general. This information might without great loss have replaced the pages devoted to the now defunct Alaska-Treadwell group.

The new edition is the product of a mature and experienced student of mining affairs and should have a prominent place in the library of anyone interested in the economic side of mining. It is, moreover, a much more useful book to the mining student than the former printings.

R. K. WARNER.

SCIENTIFIC NOTES AND NEWS[1]

C. D. WALCOTT will succeed the late Dr. Bumstead, temporarily, as active chairman of the National Research Council.

E. G. ROBINSON, instructor in geology at Cornell University, has accepted a position as geologist to the Standard Oil Company.

GEORGE C. MARTIN, of the Division of Alaskan Mineral Resources, U. S. Geological Survey, has resigned his position to become technical assistant to C. F. Bowen, chief geologist of the Standard Oil Co.

HENRY M. AMI, formerly with the Canadian Geological Survey, has gone to the south of France for a prolonged rest.

L. C. GRATON returned in February from several months of geological work at the Cerro de Pasco mines in South America. After spending a few days in Calumet, Mich., he came to New York for a brief visit.

R. P. MCLAUGHLIN has resigned as Oil and Gas Supervisor of California, and has resumed practice as petroleum engineer and geologist, at 485 California St., San Francisco.

C. P. Ross has resumed work with the U. S. Geological Survey, upon the completion of work in oil geology in South America.

O. P. BELL, of the University of Oklahoma, has been appointed instructor in Geology at Cornell University.

C. F. COURTNEY, mining engineer to the Sulphide Corporation at Broken Hill, Australia, is in London.

[1] Geologists, mining engineers and others interested in applied geology are invited to keep the editor informed of new investigations of mining districts or scientific studies undertaken by them, together with such other scientific and personal items as may come to their notice.

G. L. HARRINGTON, of the U. S. Geological Survey, has been granted leave of absence for one year beginning February 3, to engage in commercial work in South America for an American company.

GEORGE W. STOSE, of the U. S. Geological Survey, has been elected president of the Geological Society of Washington, D. C.

J. J. LILLIE has accepted a position as assistant professor of geology in the Colorado School of Mines. He was formerly superintendent for the Horn Silver Mines Co.

N. H. DARTON has returned from Mexico, and is with the U. S. Geological Survey.

E. O. TEALE has left for Tanganyika Territory to make a new geological survey for the Colonia Office of England.

D. E. LOUNSBERY, instructor in geology at Cornell University, has accepted a position with the Pearson Oil Company.

A. R. ELLIOTT, formerly assistant petroleum engineer of the U. S. Bureau of Mines, at San Francisco, has resigned to accept a position with the Pierce Oil Corporation at Oklahoma City.

G. C. BATEMAN has moved from Toronto to Cobalt, Ontario, where he may be addressed in care of La Rose Mines, Ltd.

OSCHAR LACHMOND has returned to Spokane, Washington, from China.

JOSEPH A. TAFF, previously of the U. S. Geological Survey, and geologist of the Southern Pacific Company, has been lecturer in geology at Stanford University, serving in absence of Dr. Bailey Willis during the winter quarter.

JOHN A. BURGESS has been making a geological examination at Searchlight, Nevada.

LIVINGSTON WERNECKE, geologist for the Treadwell companies in Alaska, was in San Francisco, recently.

EUGENE STEBINGER has resigned as geologist of the U. S. Geological Survey.

R. P. LUKE, mining engineer, has returned from Mexico to New York City.

D. R. THOMAS, mining engineer, has moved to Mexico City, where his address is Edificio La Mutua 522.

GEORGE E. BURTON has opened an office for consultation in Petroleum Geology, at 1216 Colcord Building, Oklahoma City, Okla.

H. A. GUESS, consulting engineer for the American Smelting and Refining Co. and the Guggenheim interests, left in February for a two months' trip to South America.

G. L. GREEN, formerly consulting geologist at Mineral Wells, Texas, is now geologist for the Marland Oil Co. of Tampico, Mexico.

A. R. MARTINEZ, of the Mexican Geological Survey, is spending the winter in Washington, studying with Mr. Larsen and other members of the Geological Survey the methods used in petrographic research.

FRANK PARSONS, formerly with the Marland Refining Co. is now geologist for the Western Oil Fields Corporation of Denver, Colorado, with an office in Oklahoma City, Okla.

O. B. HOPKINS returned to Washington from exploration for oil in Colombia, South America, and has left for Toronto.

HERBERT N. WITT has been appointed geologist to the north end group of mines on the Comstock Lode, comprising the Consolidated, Virginia, Ophir, Mexican, Union and Sierra Nevada Mines.

M. Y. WILLIAMS, of the Geological Survey of Canada, has resigned to become professor of paleontology at the University of British Columbia, Vancouver.

E. E. CAMPBELL, former assistant general manager of the Granby Co. at Anyox, B. C., has resigned to become general superintendent of United Verde Extension Mining Co., Jerome, Arizona.

T. WAYLAND VAUGHN, of the U. S. Geological Survey, has gone to Haiti, to inspect geaologic surveys being made there by the U. S. Geological Survey in coöperation with the local government.

EDWIN KIRK, who resigned from the U. S. Geological Survey, last April to undertake commercial work in South America, has been reappointed a geologist in the Geological Survey.

THE 123d Annual Meeting of The American Institute of Mining and Metallurgical Engineers was held in New York, February 14 to 17. Few economic geologists were present and papers dealing with economic geology were considerably fewer than usual. Those on petroleum geology preponderated, and the discussions which ensued were somewhat lively. The presiding officer, Dr. Ralph Arnold, stated that at the Tulsa meeting, a padded cell was to be provided for those wishing to discuss the origin of salt domes.

THE following economic papers were presented: Geology of Pachuca and El Oro, by H. V. Winchell; Alaskan coal fields, by G. W. Evans; Potash deposits of Alsace, by Hoyt S. Gale; Mexican Taxation of Petroleum, by V. R. Garfias; Modified oil-well depletion curves, by A. Knapp; Barrel-day values, by G. H. Alvey and A. W. Foster; Secondary intrusive origin Gulf Coast Plain salt domes, by W. G. Matteson; Carbon ratios of coals in the West Virginia oil fields.

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